AN ASSESSMENT OF THE OPTIONS AVAILABLE TO AIR FORCES' COMMANDERS TO SUPPRESS SMOKE FROM OIL WELL FIRES

THESIS

William B. Owens, Captain, USAF
Richard D. Taylor, Captain, USAF

AFIT/GEE/CEC/92S-16

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GEE/CEC/92S-16

AN ASSESSMENT OF THE OPTIONS
AVAILABLE TO AIR FORCES' COMMANDERS
TO SUPPRESS SMOKE FROM OIL WELL FIRES

THESIS

William B. Owens, Captain, USAF
Richard D. Taylor, Captain, USAF

AFIT/GEE/CEC/92S-16

Approved for public release; distribution unlimited

The views expressed in this thesis are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

AFIT/GEE/CEC/92S-16

AN ASSESSMENT OF THE OPTIONS AVAILABLE TO AIR FORCES' COMMANDERS TO SUPPRESS SMOKE FROM OIL WELL FIRES

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering and Environmental

Management

William B. Owens, B.S.
Captain, USAF

Richard D. Taylor, B.S , M.S.
Captain, USAF

September 1992

Approved for public release; distribution unlimited

Table of Contents

Page

Page

List of Figures

Figure | Page

Figure | Page

List of Tables

AFIT/GEE/CEC/92S-16

Abstract

The particulates in smoke from oil well fires can obscure targets and inhibit the use of precision-guided munitions. The purpose of this research was to develop a decision support matrix to aid commanders of air forces select methodologies for controlling oil well fire smoke through fire suppression. Through interviews with military experts and firefighters, a set of situational factors affecting the employment of these technologies was developed. Technologies for extinguishing oil well fires were investigated by conducting expert interviews and studying research data, periodical literature, and proposals suggesting means to control the Kuwaiti oil well fires. Over 200 proposals from the Kuwaiti disaster and four technologies from the R&D community were reviewed. The feasibility of military employment in a combat environment was determined through a bimodal evaluation of methodologies using nine criteria. Only one methodology met the criteria; diminishing the practicality of a decision matrix. The decision matrix was replaced by a ranked list of methodologies. Further research is necessary to replace the bimodal evaluation with a weighted-criteria evaluation of the methodologies. Researchers could quantify the effort required to make the methodologies employable by the military and establish a threshold past which pursuit of the technology becomes impractical.

AN ASSESSMENT OF THE OPTIONS AVAILABLE TO AIR FORCES' COMMANDERS TO SUPPRESS SMOKE FROM OIL WELL FIRES

I. Introduction

Background

On 2 August 1990, the Iraqi military invaded Kuwait. Soon after that, the Iraqi leader, Saddam Hussein, threatened to ignite Kuwait's petroleum assets if any nation attempted to drive Iraq from Kuwait.

On 16 January 1991, the United States (U.S.) and allied coalition forces began bombing Iraqi targets, and within a few weeks the Iraqis began blowing up Kuwaiti oil wells, storage tanks, and refineries (Horgan, 1991:17; Canby, 1991:12). The result was the worst single outpouring of smoke emissions in the recorded history of humanity (Horgan, 1991:24). The Kuwaiti government claimed that while the fires were burning, nearly a million tons of oil went up in smoke every day (Horgan, 1991:17).

The smoke was so thick that it blocked the sun, creating near-darkness at midday in Kuwait City, Kuwait (UNEP, 1991:978; Canby, 1991:12). The fires injected nearly 100,000 tons of soot into the atmosphere each day (Horgan, 1991:17). The prevailing winds caused the smoke to drift southeasterly in a fan-shaped plume away from the targets in Iraq that were of greatest concern to

coalition forces. If the wind direction had been reversed, the smoke plume would have seriously impeded the coalition air campaign (Warden, 1991; Robertson, 1992:92).

Initially, air operations consisted of surgical strikes against military command and control and other strategic targets in the city of Baghdad, Iraq. The F-117 fighter/bomber and precision-guided munitions were used to minimize collateral damage during the attacks. (In this context, collateral damage is destruction/injury of non-targeted facilities, equipment, or personnel that are not the intended targets of the attack but are damaged/harmed as a result of proximity to the target.)

While this effort continued, other allied air assets were used to destroy the Iraqi ground forces deployed in the field to repel advancing coalition ground forces. On the open battlefield, less precise weapons were used because of reduced concern for collateral damage. In both the city and on the more exposed battlefield, the success of air operations hinged on the pilots' ability to locate targets.

General Issue

A large portion of the success of air forces is measured by their ability to control air space and accurately hit targets. The effective employment of nearly all of the air platform-deliverable weapons in the United States' inventory relies heavily upon aircrew members' ability to "see" the target (Phillips, 1992;

Robertson, 1992:93; Hughes, 1987:6.37; Hughes, 1988:1.16,2.1). For each weapon system, targets must be seen using either the naked eye or images of targets that are electronically depicted on screens in the cockpit. If an obscurant, such as smoke, can prohibit the visual acquisition or electronic transfer of the target image, the target cannot be seen or acquired, and thus cannot be effectively struck (Sikes, 1992). Senior coalition planners, aware of these facts, were concerned by Iraq's threat to ignite Kuwaiti oil wells (Warden, 1991).

Future weapons modifications may eliminate the problems that smoke poses to the effective employment of air platform-deliverable munitions currently in the U.S. inventory. New weapons not affected by smoke may be fielded. A Statement of Need for a new all-weather weapon was approved by the Joint Requirements Oversight Council which opened the door for the development of such a weapon (Tactical, 1991). But, until either the current munitions are modified or new systems are fielded, the elimination or control of smoke on the battlefield is a salient issue for commanders of air forces. Air campaign planners and commanders must have sufficient knowledge of options at their disposal for abating smoke. This is critical if they are to make the time-sensitive decisions that are necessary for preventing smoke from becoming an impediment to air operations.

Research Objectives

The purpose of this research was the development of a decision support matrix to help commanders of air forces select the best option for controlling smoke from oil well fires affecting air-to-ground operations in a combat environment. The final product, the matrix, was pursued by accomplishing four tasks.

First, exhaustive research was undertaken to identify all methods that might be employed for fire suppression. Data about existing technologies, as well as technologies in the research and development stages, were obtained from periodical literature, professional journals, primary research documents, and from personal and telephone interviews. Second, these technologies were compiled and those applicable to oil well fires were extracted for further study. The criteria for this sorting came from information gathered during a comprehensive literature review and from expert consultation. Third, the remaining technologies were analyzed for their applicability to military employment in the combat environment. Department of Defense (DOD) experts in relevant fields and services were consulted to ensure applicability for military use.

Finally, situational factors were listed that pertain to the area of concern (i.e., do we have air superiority, do we have control of the immediate battle area, is there a need to preserve the wellhead, are trained personnel available,

and is adequate equipment available) and could affect the application of the technologies under review. This information was acquired by interviewing personnel knowledgeable in oil fire suppression or military operations.

The decision matrix was to be developed by placing on the horizontal axis a list of possible oil well fire suppression alternatives employable during wartime by the military. A list of situational factors that a commander should consider when attempting to apply those technologies was to make up the vertical axis. The resulting matrix could aid air forces commanders in determining options for suppressing smoke from oil well fires that is adversely affecting the execution of air battle plans.

Scope/Limitations

1. The research only concentrated on three-dimensional petroleum (petroleum under pressure) fires; specifically, oil well fires which produce immense amounts of extremely dense smoke and steam.

2. Discussions of methods used to ignite the fires and descriptions of methods of oil exploration, exploitation, and production were outside the scope of this paper.

3. The research focused on technologies that can be effectively implemented by DOD personnel without the assistance of civilian company specialists. This was primarily due to the legal ramifications of having noncombatants on the battlefield.

4. The research was not limited to "off-the-shelf" technologies. New and innovative technologies were also investigated.

5. Weapons descriptions and limitations are at the unclassified level.

6. The munitions guidance systems of primary interest to this research were those most significantly affected by burning petroleum smoke. These were laser, television (TV) and infrared (IR) munitions guidance systems. Radar-guided weapons and those requiring the Global Positioning System (GPS) are less accurate and, with few exceptions, not affected by smoke.

7. Although suppression of smoke was the primary focus of this paper, it was assumed that smoke can best be eliminated by extinguishing the petroleum-fed fire.

Summary

Chapter II presents a more detailed discussion of the effects smoke has on target acquisition on the battlefield. Additionally, it includes a description of the conventional technologies currently used to suppress oil well fires. Chapter III describes the research methodology employed to compile possible alternatives for suppressing oil well fires in a contingency/combat environment. Findings and an analysis of the research, followed by the development and presentation of a decision matrix are presented in Chapter IV. In Chapter V, the research is summarized, followed by conclusions and recommendations for further research.

II. Background

Introduction

The purpose of this chapter is to provide extended background on the subject of this research. First, the adverse effects of smoke and other obscurants on acquisition systems of air-delivered munitions are discussed. Next, typical oil well configurations and the associated production hardware characteristics are described followed by a presentation of conventional oil well fire suppression strategies. The procedures discussed are those conventional methods most commonly used by civilian oil well firefighting organizations around the world. These methods were used in the Kuwaiti oil fields to extinguish over 600 burning oil wells (Wadley, 1992).

Effects of Smoke on Weapons Delivery

The use of smoke as an obscurant has been found to be an effective concealment tactic, even among today's technologically advanced militaries (HQ PACAF/DOU, undated). "Obscurants such as dust, smoke, haze, fog, rain, drizzle and clouds . . . give the enemy sanctuary from which he may further his combat objectives" (Tactical, 1991).

> The firing of oil wells to create thick, black palls of smoke by Iraqi forces in Kuwait probably was prompted - at least in part - by the hope of rendering Western lasers and thermal imagers ineffective. (Tusa, 1991:36)

The composition of the smoke plumes from the oil well fires obscured the operational spectrum of many target acquisition systems. The degree to which systems were affected depended on the particle size of the soot, water, and chemicals in the emissions. The visible spectrum falls in the 0.38 to 0.78 micron waveband. Today's target imaging devices operate in the 0.2- to 12-micron range. TV imagers operate in the 0.2 to 2.0 micron range; IR imagers primarily operate in the 8- to 12-micron range (though some are effective in the 3- to 12-micron range); and laser designators operate at 1.06 microns (Tusa, 1991:36; Air, 1984:3-5 - 3-15; Smith, 1980:34).

The smoke plumes from the Kuwaiti oil well fires covered areas from 7,100 to 180,000 square kilometers. The average particle size in the plumes was approximately 1.0 micron. This particle-size distribution resulted in severe degradation in unaided visibility and, depending on the density of the particulates, could have potentially reduced the effectiveness of TV imagers and laser designators. In the ambient atmosphere, opacity increased in the 3.7- to 10.9- micron range (Limaye, 1991:1536).

> The increased particle sizes [into the IR waveband] were due to the intrusion of water into the oil wells and as a combustion product and condensation onto the smoke particles. (Limaye, 1991:1536)

Thus, the smoke from the oil wells had the potential to obscure the waveband (from 1 micron to 11 microns) in which the U.S. military's primary target acquisition systems operate. This proved to be the case with IR and TV

imagers used in the Kuwaiti Theater of Operations (KTO) among the burning oil wells.

At the tactical level, allied air forces (F/A-18A/C/Ds, AV-8Bs, and A-10s) performed battlefield air interdiction (BAI), forward air control (FAC), and some close air support (CAS) on the battlefront where the burning oil wells "severely affect[ed] air operations" (Robertson, 1992:92). "The obscurants in the air made visibility poor, drastically reducing . . . [the pilots'] ability to see ground events" (Robertson, 1992:94). Also, the resolution of the targeting forward looking infrared (TFLIR) sensors (the primary acquisition system used in the KTO) was significantly reduced due to smoke and humidity (Robertson, 1992:91-93).

Immediately prior to the Gulf War no one knew exactly how the smoke from the burning wells would affect military operations, but the air campaign planners quickly discovered that the military had no means of dealing with these fires (Taylor, 1990). Due to the northwesterly winds over Kuwait, the smoke from the burning wells was blown away from Iraq and presented no long-lasting interference to either air or ground operations (Tusa, 1991:36; Robertson, 1992:92). However, many questions were never answered. What if the smoke had significantly affected combat operations at the strategic level? In what ways was it most likely to have affected those operations? And, for the

purposes of this research, what technologies can be applied to suppress this type of smoke in the combat environment?

Oil Well Design

There are broadly differing configurations of oil wells around the world. Most of the differences are a result of the location of the geologic formations - not of basic production hardware design. For the purposes of this research, a typical oil well is similar to one found in the Burgan oil field in Kuwait. This typical oil and gas well is about 5,000 feet deep, and requires drilling up to six consecutive holes; each one smaller in diameter and deeper than the one preceding it (Garwin, 1991:11). When looking at a profile of the well, it has a telescopic appearance with each successive casing going from the surface deeper into the earth (Figure 1). When looking at a cross section of the well from above, it appears as five concentric rings (Hatteberg, 1991)(Figure 2).

The first hole drilled is 26 inches in diameter and about 30 feet deep. A 20-inch diameter piece of pipe called the conductor casing is suspended and centered horizontally by spacers in the hole. Concrete is then injected into the pipe and forced down the pipe with a plug. As this plug is forced down the inside the pipe, the concrete is forced out of the bottom and back up the outside of the pipe, all the way to the surface of the earth where it is allowed to harden. This effectively attaches the casing to the surrounding earth (Simms, 1991). Next, a 16-inch drill is lowered into the casing to bore through the plug and the

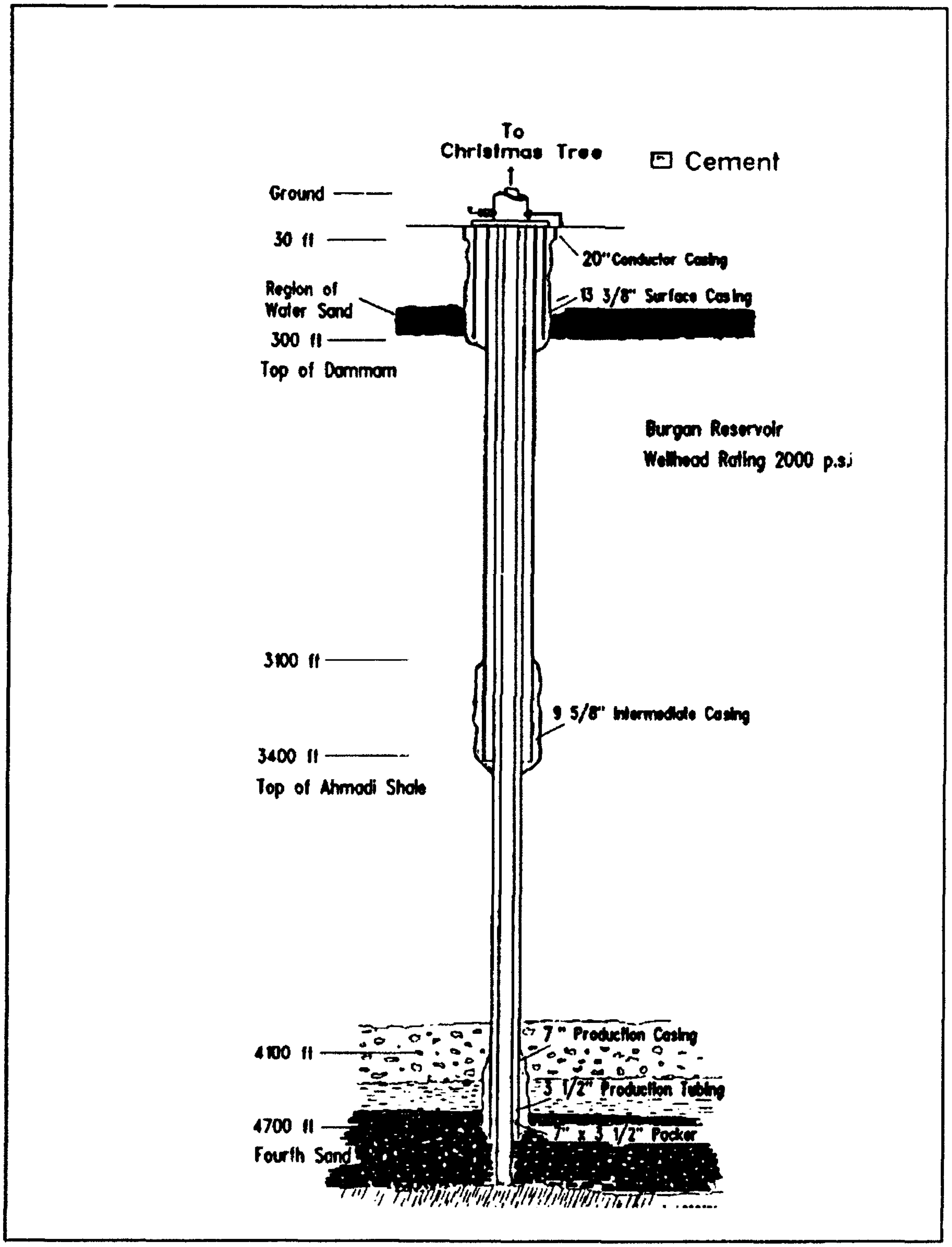

Figure 1. Oil well casing and production string configuration (Garwin, 1991)

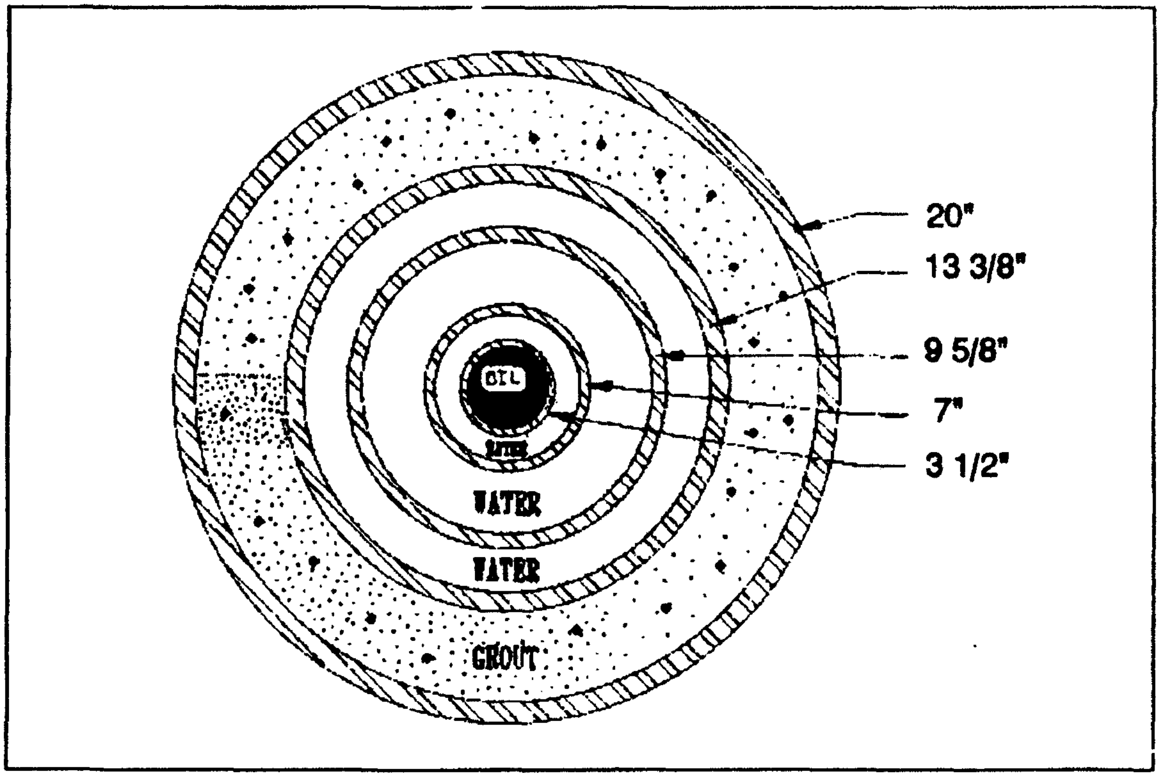

Figure 2. Cross sectional view of the well casing and production string (Component, 1991)

concrete at the bottom of the 20-inch casing. The drilling then continues for another 300 feet. The drill is removed and a 13 3/8-inch piece of pipe called the surface casing is lowered into the 20-inch casing and the 16-inch hole below, where it is suspended and centered in place with spacers. Concrete is again pumped into the smaller pipe to attach it to the surrounding earth. This process is then repeated, this time going about 3200 feet with a 9 5/8-inch intermediate casing. The last drilling process is similar, using 7-inch production casing that extends down to the reservoir of oil or gas. The last piece of pipe,

known as the production string or production tubing, is 3 1/2 inches in diameter and is suspended inside the production casing.

The production tubing and casing are suspended by a flange at the well head. A collection of plumbing consisting of flow control valves and associated safety equipment is bolted onto the flange. This entire above ground apparatus is called a christmas tree (Figure 3). The christmas tree sits in a concrete pit, called the cellar, that is about 6 to 10 feet square (or round) and 5 feet deep (Simms, 1991).

Oil Well Fires - Characteristics and Problems

When an oil well fire is burning, often an explosion has occurred, which usually means the flange and valve assemblies are damaged or destroyed. When this happens, the production casing and production string may have fallen free into the well and one or more of the casings could be damaged (Garwin, 1991:12). As a result of the many variations in the types of damage that may occur to the wellhead and/or christmas tree, no single solution exists for putting out the fire. "Because each situation is different from the last, the approach used is always tailor-made to the problem" (Adair, undated:5).

Current Technologies for Oil Well Fire Suppression

Although there are many types of oil well fires, fire extinguishing involves only a few basic activities. Technicians clear and cool the area around the well head, extinguish the fire, and control the flow of oil with high density

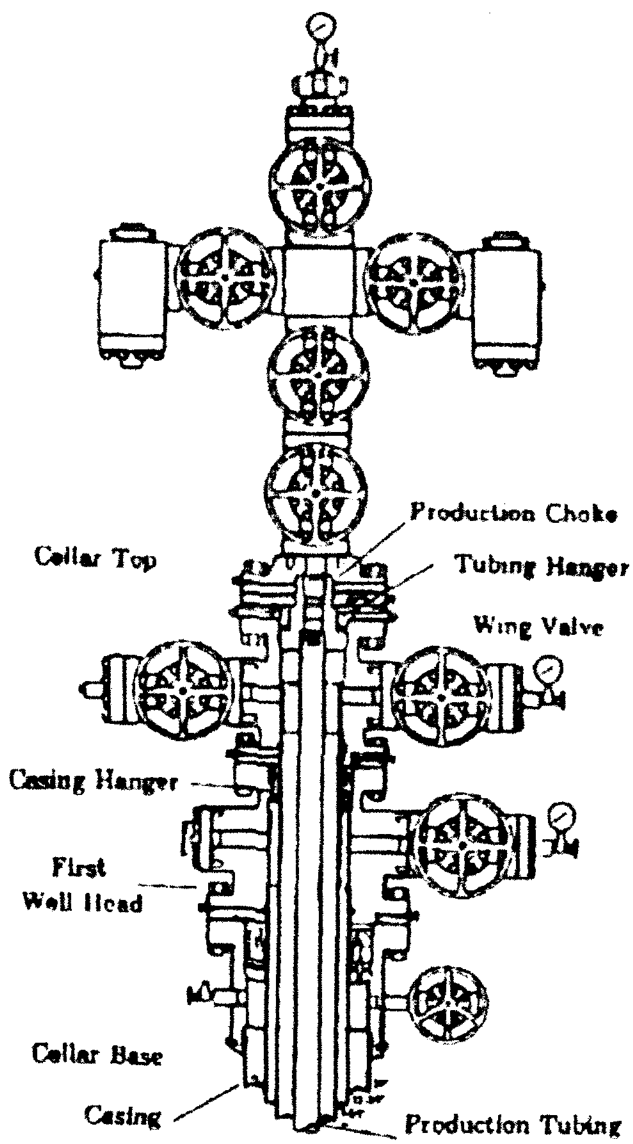

Figure 3. Christmas tree (Garwin, 1991)

muds and valve assemblies. To clear the area around the well head, first, firefighters use a hook or rake on the end of a long boom called an athey wagon (Figure 4) to remove torn metal and wreckage. This wreckage normally consists of the christmas tree and piping (Leabo, 1991). As the fire burns, a large glass-

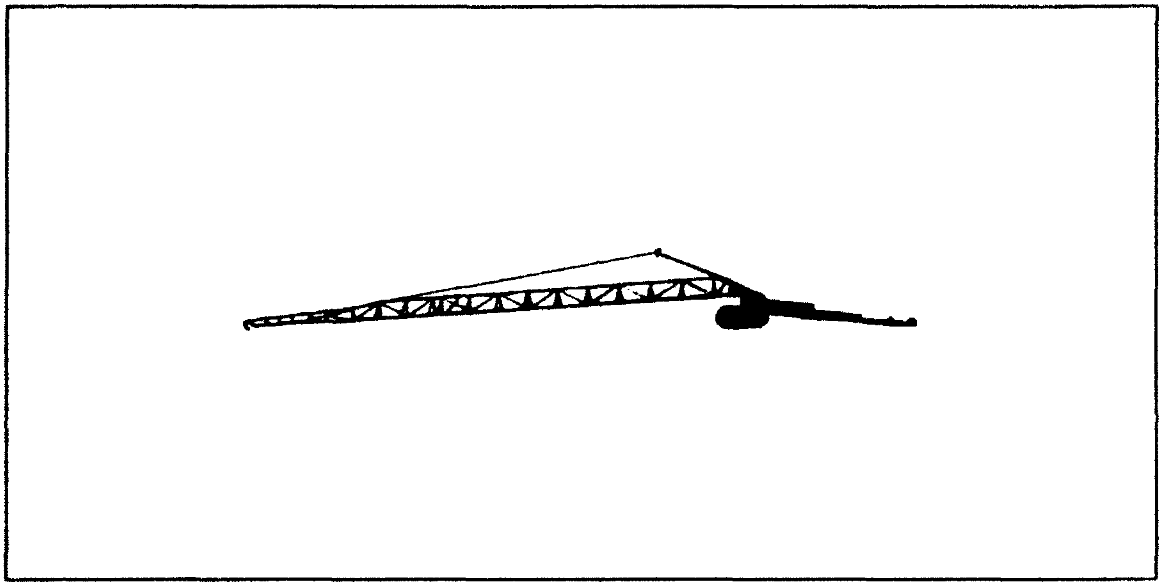

Figure 4. Athey wagon (Red, undated)

like buildup of coke, ash, and slag forms a discontinuous cone around the burning hole. Technicians also remove this cone with the rake. These steps clear the way for the well control specialists to gain access to the remaining casings or flanges (IMAX, 1992).

To cool the area close to the well head, workers spray thousands of gallons of water per minute onto everything in the proximity of the fire. If the

ground and everything in the vicinity of the well head are not cooled, the chances increase that the oil and gas will be reignited by the super-heated soil and debris. The cooling also allows fire fighters safer and more immediate access to the well head (Leabo, 1992).

Once workers clear and cool the area around the well head, firefighters employ one or more means of extinguishing the fire. Three conventional methods currently used to suppress oil well fires are the use of high explosives, a vortex tube, and a stinger.

<u>High Explosives</u>. Historically, specialists extinguished oil well fires with explosives. Typically, a carefully shaped explosive charge (usually dynamite) in a 55-gallon drum is placed on the end of the athey wagon boom and inserted almost directly in the flames over the burning well. Jets of water are directed onto the barrel to keep it cool and prevent premature detonation of the explosive. Specialists detonate the barrel of explosives once all personnel are clear of the area (Hatteberg, 1991). The explosive force often extinguishes the flames while the raw oil and gas continue to flow. Ideally, the surrounding area is sufficiently cooled to preclude reignition and allow the well control process to begin. The control process is called killing and capping the well. To kill the well, technicians pump high density mud down the production string. When the hydrostatic pressure of the mud exceeds the pressure of the oil and gas, the oil stops flowing. At this point the well can be capped with a metal cover and

gauge assembly until technicians can rework the well to bring it back into production.

Although the use of high explosives is common, this option is inherently dangerous to personnel and material at or near the well head (Garwin, 1991:12).

Vortex Tube. The use of a vortex tube is a method of oil well fire suppression that is growing in use. A 35- to 40-foot section of pipe, 18 to 36 inches in diameter, called a vortex tube, is attached to the athey wagon boom in a vertical position and moved into place directly over the flow. The oil and gas are blown up the vortex tube. This moves the flames 40 feet into the air causing the system to resemble a large Bunsen burner (IMAX, 1992) (Figure 5). Because additional air is now available to the mixture, the oil and gas burn more completely and result in significantly less smoke. This allows the well head area to cool and allows access to the well to control the flow of oil and gas (Leabo, 1992). After the area around the well head is cooled, a stream of water, or in some cases liquid nitrogen, is injected into the base of the vortex tube which rapidly extinguishes the fire. Once the fire is out, oil flow control procedures begin, and the well is killed and capped (Parry, 1992).

Stinger. Burning wells are also extinguished using a stinger. This device is made up of a hollow, conical piece of metal into which a two-inch diameter pipe is threaded (Figure 6). Attached to the other end of the pipe is a flow-through tee and a valve assembly. The stinger length ranges from eight inches

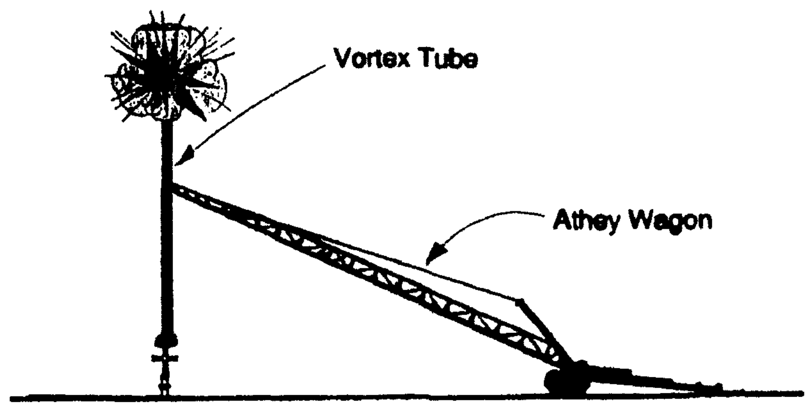

Figure 5. Vortex tube on athey wagon

to five feet long, depending on how far down into the casing the flow string has dropped (Leabo, 1992). The stinger is attached to the end of the athey wagon boom in a vertical position and situated over the exposed production tubing and well casing. The tapered end is then carefully forced down into the production string, forcing the flow of the oil and gas through the stinger (IMAX, 1992). It is held in place by exerting up to 13,000 pounds of force with the boom of the athey wagon. The control valve on the stinger is then closed, shutting off the flow of oil and gas and allowing technicians to kill and cap the well.

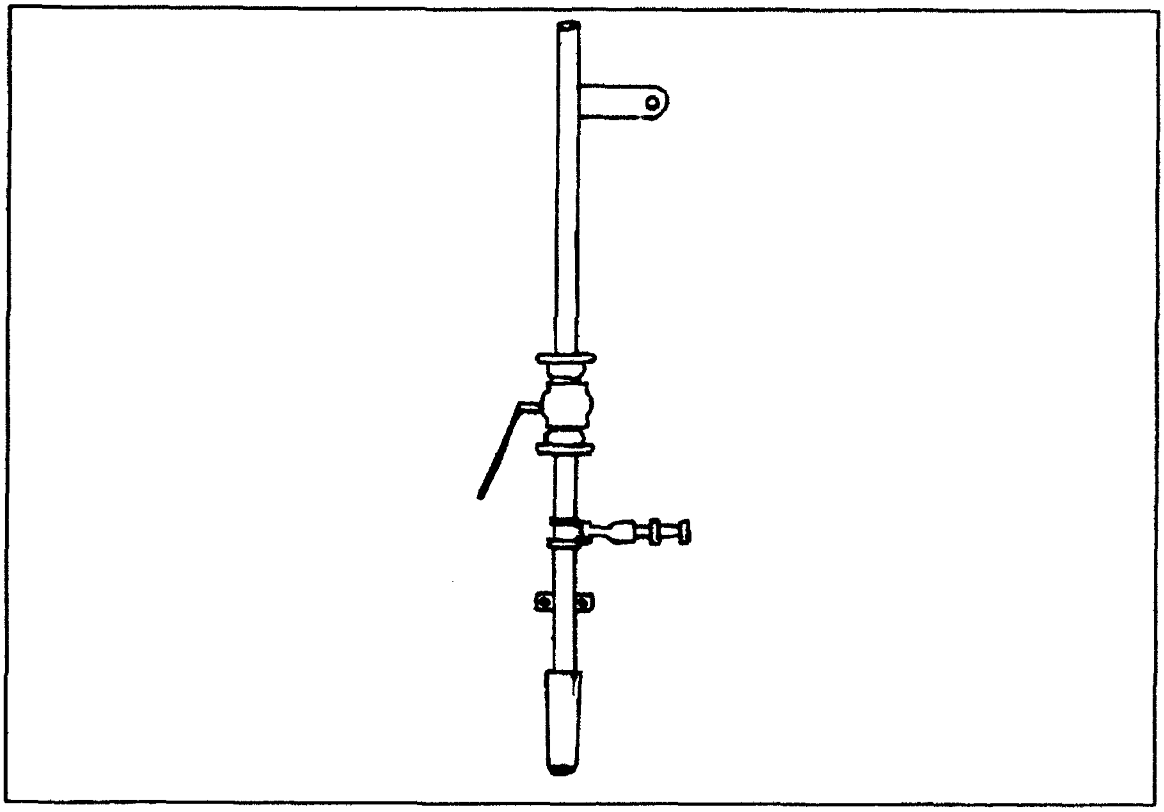

Figure 6. Stinger

These three methods of fire suppression are described separately, but in fact, they are occasionally used in combination.

In the past, the U.S. military had little need to develop or maintain the capability to perform the fire suppression operations just described. The military does have firefighting equipment designed for suppression of structural, aircraft, and vehicular fires (Floden, 1991). Additionally, the U.S. Army has developed specialized equipment to extinguish two dimensional or pooled petroleum fires (U.S., 1991). Some of this firefighting equipment might be used

to successfully extinguish oil well fires having extremely low rates of flow (Floden, 1991).

Summary

Pilots must be able to "see" targets to strike them successfully. This is true with nearly all of the weapons in air forces' inventories today. One of the prime limiting factors to a pilot's visibility on the field of battle is smoke. One source of smoke that could obscure targets is the dense concentration of particulates and gases that result from the burning oil and gas from oil wells.

Most of the oil well structure is below ground. The control mechanisms and safety equipment are above ground and most susceptible to damage. When damage occurs above ground, ignition of the oil and gas can follow. When the petroleum is burning, the christmas tree is difficult to access because of the resulting heat. Overcoming the access problem and gaining control of a burning oil well requires a combination of specialized skills and technologies that are available from only a few organizations in the world. Unfortunately, the U.S. military has a very limited capability for fighting oil well fires.

The next chapter discusses the research methodology used to obtain information regarding technologies the military might employ to reduce or eliminate the smoke resulting from burning oil wells.

III. Methodology

Introduction

The research methodology was structured to meet the research objectives provided in Chapter I. First, a search for technologies with the potential to extinguish large fires was conducted. Next, from the results of that search, technologies with the potential for extinguishing oil well fires were extracted, and technologies specifically designed to extinguish oil well fires were investigated. Finally, the resulting set of technologies (those with the potential for extinguishing oil well fires) was analyzed to obtain those technologies employable by the military in a combat environment.

Oil Well Design and Operation

Before the first objective was pursued, a sub-objective was established: to gain some understanding of oil well design and operations. Unstructured telephone interviews provided abundant information on oil well operations and resulted in finding several experts willing to cooperate with the research. These telephone interviews also proved fruitful in obtaining sources of innovative fire suppression technologies (Objective 1). Also, on-site investigations in U.S. oil fields provided further insight to oil well design and operations.

Fire and Oil Well Fire Suppression

While the effort to gain general background information on oil wells was taking place, unstructured telephone interviews and a comprehensive literature search were used to gather information on existing and new, innovative technologies for fire suppression (Objective 1) and oil well fire suppression (Objective 2). Information on both was found in journals and periodicals, and further researched through personal and telephone interviews.

Primary research data from the Shock Physics Division of the Phillips Laboratory at Kirtland AFB NM, the Air Force Civil Engineering Support Agency at Tyndall AFB FL, and from Air Force research contractors in the private sector were investigated. These organizations provided information on several technologies for both fire suppression and oil well fire suppression.

The Kuwaiti oil well fires were still an issue of concern at the time of the research. Extensive film and television coverage were plentiful and provided additional understanding of the problems and concerns relating to oil well fire suppression.

In addition to information gained from domestic media, a wealth of information on oil well fire suppression technologies was obtained from the Kuwaiti Petroleum Corporation (KPC) in Kuwait City. KPC approved and arranged for interviews of its personnel in the field and granted access to its archives of data gathered during the firefighting effort.

Access to the oil fields of Kuwait afforded invaluable knowledge of the equipment and the environment associated with the Kuwaiti oil well crisis. Firefighters who fought the Kuwaiti oil well fires were interviewed in-depth to gain an understanding of the methods used to suppress the fires. These knowledgeable individuals also provided valuable input in achieving Objective 2. They gave insight in determining which fire suppression technologies obtained from achieving Objective 1 might be extracted for having the potential to extinguish oil well fires.

While the oil well fires in Kuwait burned, firefighting and engineering organizations from around the world submitted offers to KPC to assist in the extinguishing efforts. In London, England, these proposals were reviewed by two committees.

The first committee reviewed the offers of teams planning to use conventional methods of putting out the fires. The teams were judged on a number of elements, the most significant of which was experience. Companies meeting the first committee's criteria were hired to assist in the firefighting effort.

A second committee was formed to review proposals for putting out the oil well fires using nonconventional means. This team judged the merits of the offerers' proposals using a variety of criteria. Among the criteria were appraisals of the likelihood the method could extinguish the fire, the time

required to field and apply the suggested method, the likelihood of compounding the problems at hand by further damaging the oil well, and finally, the cost of applying the proposal. Hundreds of proposals were submitted by well-known, as well as previously unknown, organizations and individuals worldwide. The proposals and other materials became a major portion of the firefighting archives.

Criteria for Determining Military Applicability

As part of the research effort the data in the KPC archives were reviewed. These proposals were compiled with the technology-related data obtained in the U.S.. Together, those that previously met the criteria of the first two objectives were evaluated against the following criteria for military applicability in a combat environment.

1. The suggested technology must result in a significant reduction of smoke, whether the fire is extinguished or not.

2. The price of research, development, design, and fielding of the proposed technology must be so low as to be negligible. The climate of reduced military spending will not permit significant expenditures for a short-lived program.

3. The training of personnel to operate the new system must be within the scope of current training. Due to the low probability of use, it is not

realistic or cost-effective to establish new schools requiring additional manpower and extensive curricula development.

4. Off-the-shelf military equipment should be used to the greatest extent possible. This reduces added logistics support requirements and utilizes existing maintenance skills.

5. The primary equipment must be durable and field worthy. It must withstand an environment of high temperatures, spewing oil, and mud. The equipment must also operate on unimproved surfaces.

6. The equipment must be portable, highly mobile and of such size as to be air transportable in military aircraft.

7. Once deployed, the equipment must be capable of being set up and employed within hours or at most a few days.

8. Similarly, support equipment and the training to operate it must meet the above training and equipment criteria.

9. The technology must be of such a nature that personnel are not placed in grave jeopardy by either proximity or use.

Ancillary concerns that are desirable but not critical follow:

1. The system should minimize environmental and ecological damage to the air, water, and land to the greatest extent possible.

2. The technology, when applied to, in, or around the well head, should result in minimal subterranean damage to the well itself. The goal is to enable

the well to be brought back into production with minimum effort and expense after the conflict.

Summary

The applicability of nonconventional technologies by the military in combat was difficult to assess as there were no experts in this specific area. This required the proposals be evaluated by military experts in the various services' engineering, fire suppression, logistics, and operations arenas.

This list of criteria became the means by which the proposals were evaluated. Proposals that met all the above criteria were to become elements of the vertical axis of the decision matrix. These technologies would be able to (1) extinguish fires, (2) extinguish oil well fires, and (3) be employed by the military in a combat environment. The technologies, coupled with the situational factors on the horizontal axis, were to serve as a simple, effective decision tool for commanders.

In the next chapter the variations of each technology are described in detail and evaluated for their ability to meet the above criteria.

IV. Descriptions and Analyses

Overview

In this chapter, seven technologies for suppressing the smoke from oil well fires are presented. They are:

1. crimping the production string
2. applying chemical agents
3. applying an electro-static energy field
4. freezing the flow to form an ice plug
5. hot tapping to block the flow of oil
6. using hoods or domes
7. using wind producing devices.

Several methodologies use to employ each of these technologies are presented. The description of each methodology is followed by an analysis based on the criteria presented in Chapter III. This is followed by a discussion focused on the use of the ancillary criteria to select the best methodology in the event that two options are equally acceptable. The chapter concludes with a discussion of the relative ranking of the methodologies based on the analyses using the nine primary criteria.

Analysis of Methodologies Using Primary Criteria

No attempt was made to assign weights to the nine criteria. Due to the short time span in which the fire suppression technology has to be fielded and the low probability of its use, it is infeasible to spend time or funds to develop a new capability. Thus the analysis is bimodal; either the criteria is met or it is not.

Description of Crimping Technologies. Extinguishing oil well fires by depriving the flame of fuel is the essence of crimping. Crimping the production string to stem the flow of oil and gas is a method that has numerous variations. Government entities, as well as private organizations in the U.S. and abroad, proposed methods of applying this technique for extinguishing oil well fires to the Kuwaiti Petroleum Corporation (KPC) during Desert Shield/Storm (Al-Rahmani, 1992). Crimping can be accomplished using either high explosives or mechanical devices to compress the production string.

High Explosives. The use of high explosives involves detonating charges at specific locations in the proximity of oil well casings.

> The resulting shock wave (pressure wave) is transmitted through the earth, surrounding the well, causing the complete crushing of the casings, including the production tubing - if it is still in place. (C.O.R.T., 1991:111)

Since the well head sits in the cellar and is at about ground height, all efforts to employ crimping must take place at or below grade. The means of

delivering the explosive material to the designated position may vary, but the charges are either detonated at ground level or below ground level.

Surface-Detonation. Surface-detonation methods require that technicians have access to the area around the well head. These methods are expedient and considered safer than some other methods (C.O.R.T., 1991:56).

A proposal by the Michael Stewart Group International of Nottingham, England, suggests that a vortex tube with a heat shield be employed once the christmas tree is removed (Figure 7). With this in place, excavation of the area around the well head is accomplished, and a pristine section of well casing is exposed (Freeze, 1991:5). Explosive charges are then brought into position around the well casing (Figure 8) and "a series of small controlled detonations will be made to crimp the stand pipe . . . " (Freeze, 1991:9)(Figure 9).

The International HYDROCUT Technologies Corporation of Vancouver, Canada, suggests placing explosive charges that would both excavate a crater, allowing access to the undamaged well casing; and crimp the casings, shutting off the flow of fuel feeding the flame (C.O.R.T., 1991:39). The charges are specially configured tanks moved into place around the damaged well head by a remotely operated and shielded vehicle (Figures 10 and 11)(C.O.R.T., 1991:39).

> The tank or charge consists of an explosive element surrounded by an inert liquid . . . designed to crimp below ground level. The explosive element could be solid, liquid, foam or slurry in composition. (C.O.R.T., 1991:49)

The designs presented in Figure 12 use inert fluids and explosives. The fluid and the soil immediately around the fluid serve specific purposes.

First, the fluid limits the detonation by providing a barrier between the explosive products and the surroundings. This serves to direct and control the explosive forces and create a more uniform, flat-bottomed crater. Secondly, the focused blast energy provides for more efficient cratering. The "craters produced are an order of magnitude larger than those created with the same amount of explosive but without liquid enhancement" (C.O.R.T., 1991:53). The fluid is positioned between the explosives and the well head, and protects the already damaged well head from further harm. Finally, the fluid serves to cool the explosives from the time they are injected into the tank-like charges until they are detonated (C.O.R.T., 1991:50-53).

Finally, the "soil functions as a medium for the transfer of explosive energy to the well casing" (C.O.R.T., 1991:50) and is also the protective medium that separates the well casing from the scouring effects of the explosive material. It also attenuates the concussion along the length of the well casing which results in effects that range from no damage, at greater depths, to total crimping and even possible destruction of the casing at or near the well head (C.O.R.T., 1991:50)(Figure 13).

The proposal by International HYDROCUT Corporation anticipated the possibility that the surface crimp might need some follow-on work.

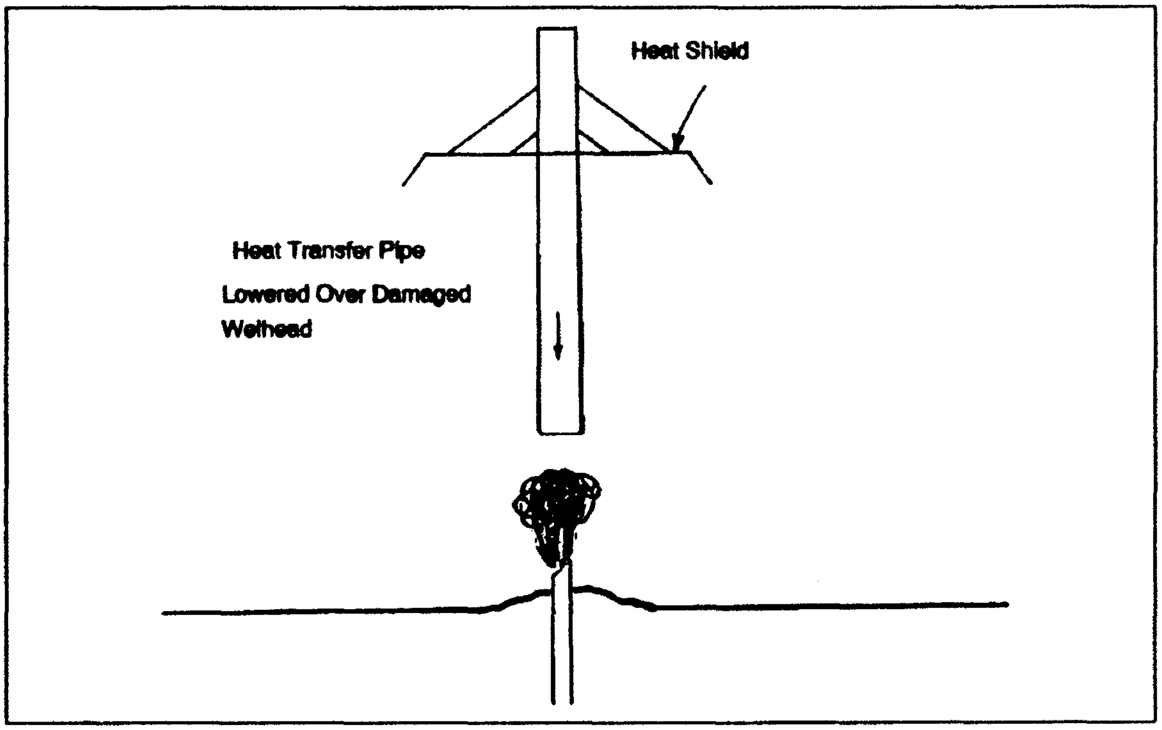

Figure 7. Vortex tube with heat shield (Freeze, 1991:7)

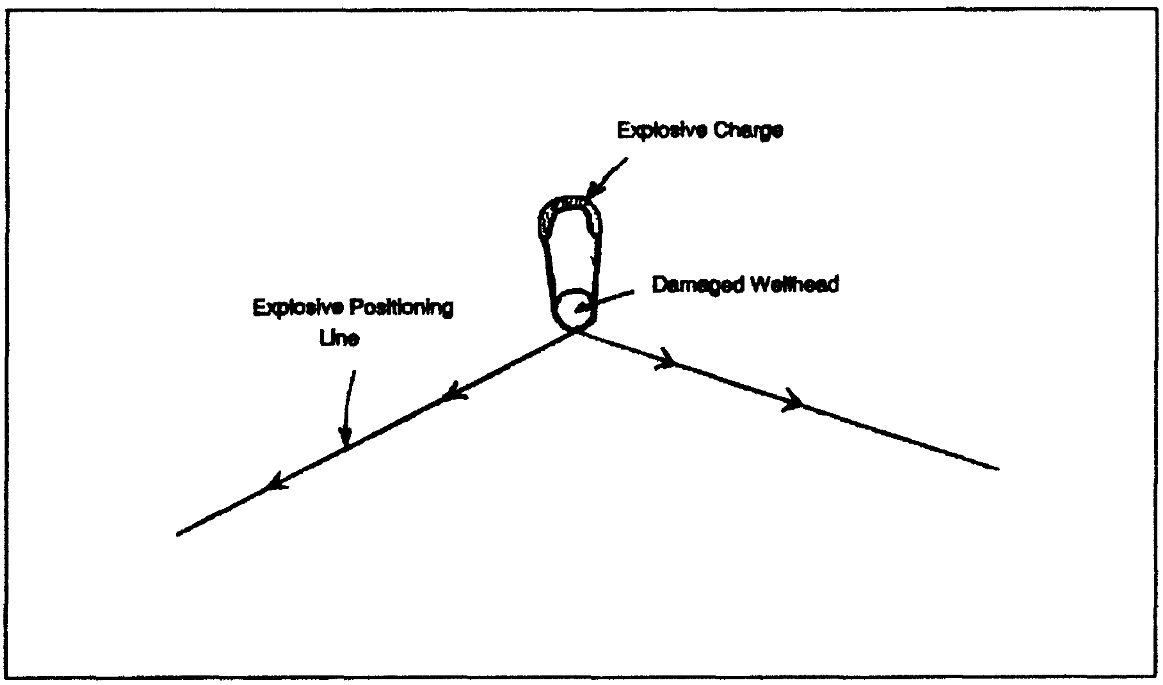

Figure 8. Explosive charge is pulled to the damaged well head (top view) (Freeze, 1991:9)

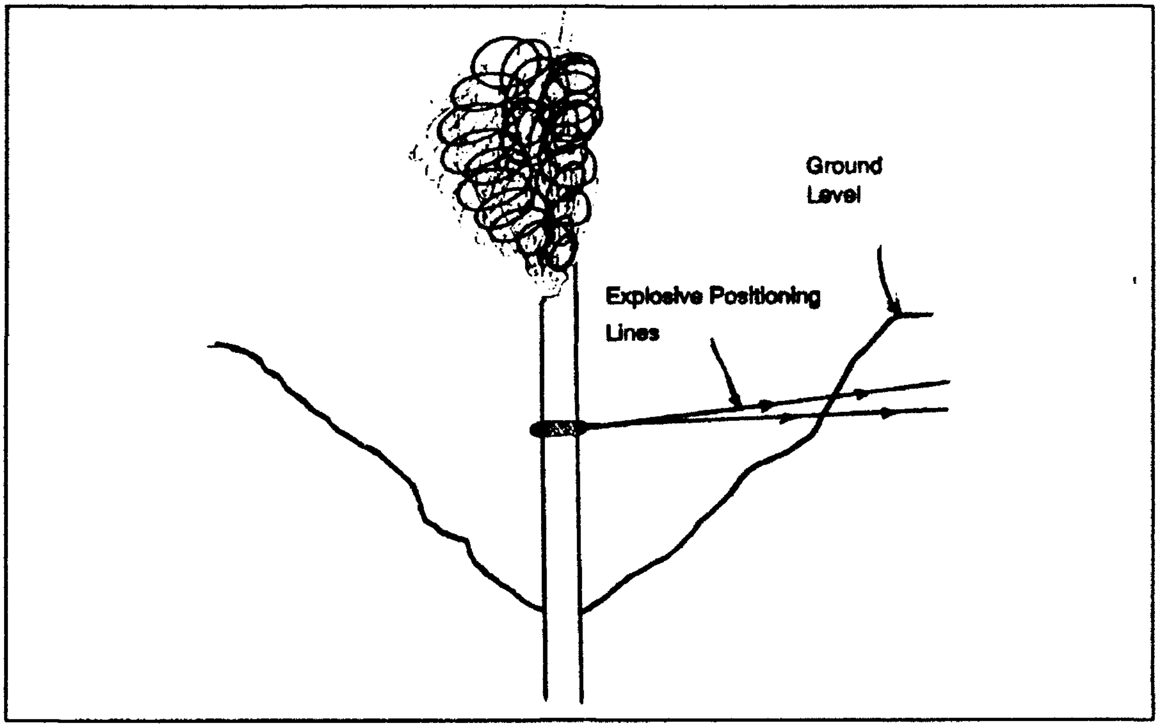

Figure 9. Detonation takes place once the explosive is positioned around well head (side view) (Freeze, 1991:8)

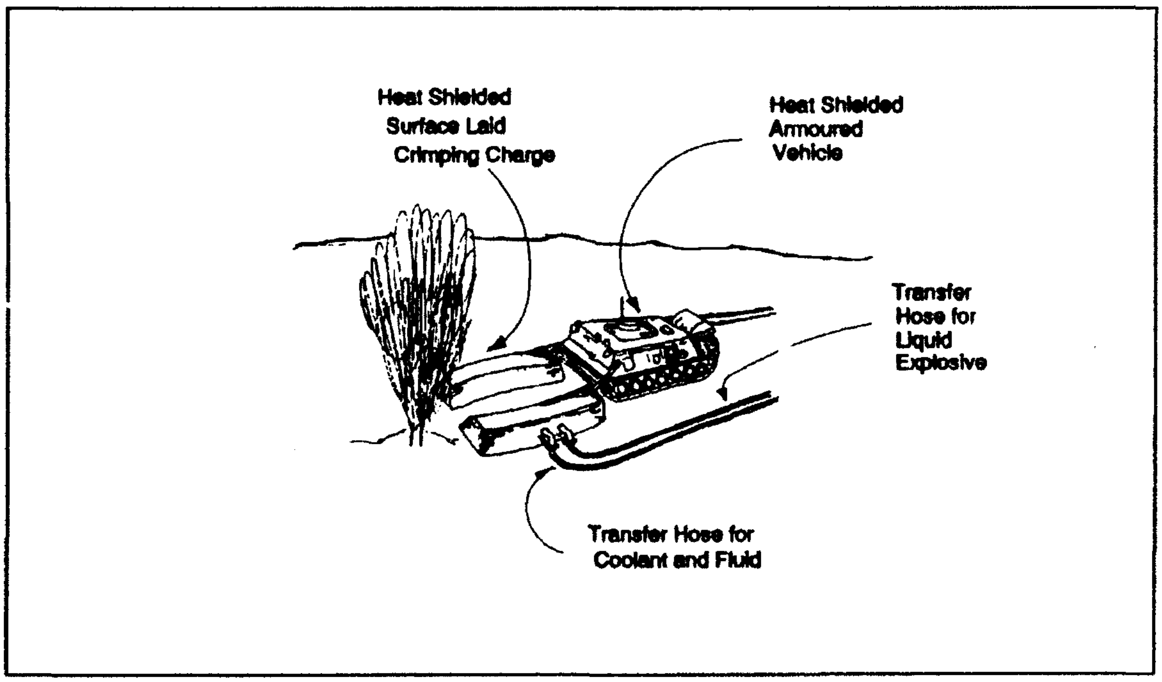

Figure 10. Emplacement of Surface-Laid Crimping/Cratering Charge around damaged casing (C.O.R.T., 1991:Fig 4)

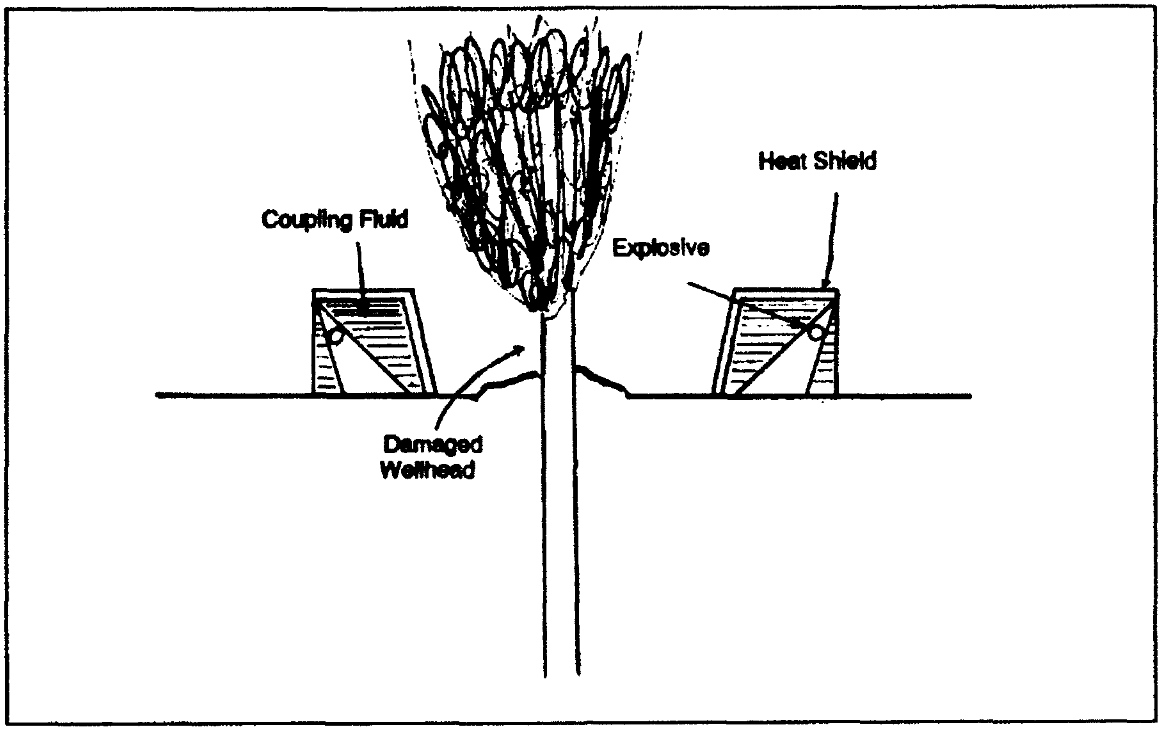

Figure 11. Surface charge in place (C.O.R.T., 1991:Fig 2)

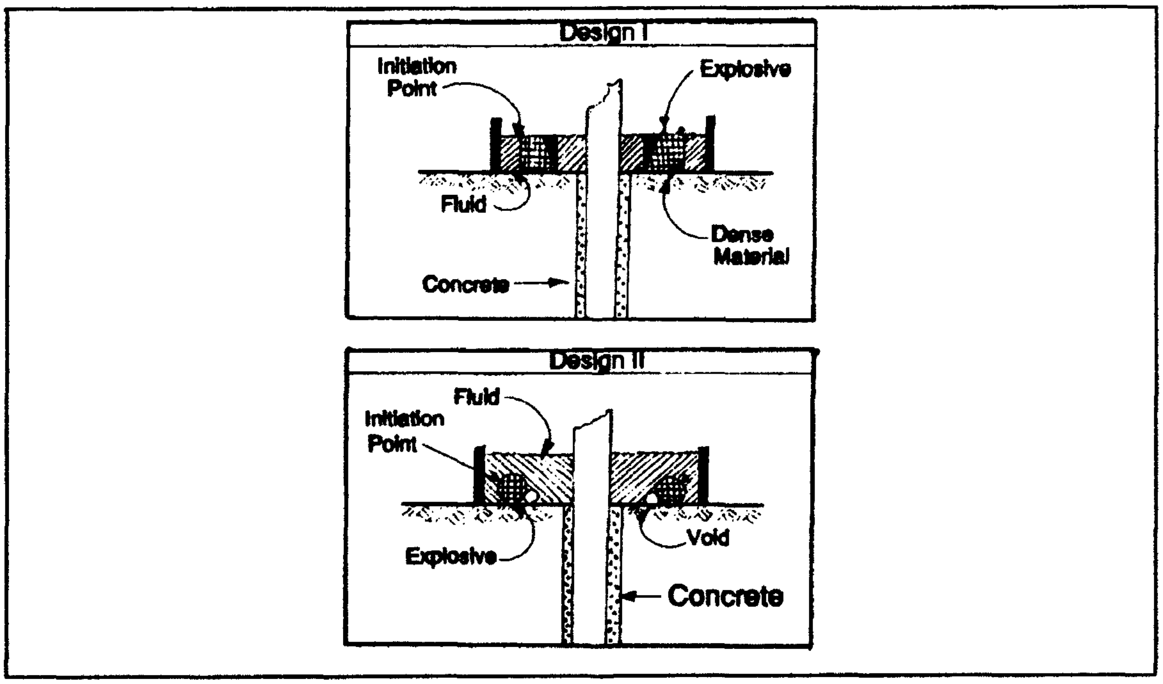

Figure 12. Schematic showing the features of the Surface-Laid Crimping/Cratering Charge (C.O.R.T., 1991:Fig 1)

With that in mind they designed a crimping charge similar to those in Figure 12 that can be placed around exposed well casings (Figure 14). These charges are much smaller and make it easier to control the type and degree of crimp (C.O.R.T., 1991:59-65).

The methods allowing surface detonation hold many advantages, but the disadvantages inspired engineers and scientists to search for sub-surface alternatives.

Sub-surface Detonation. These methods involve detonating charges below grade to crimp the production string (Figure 15).

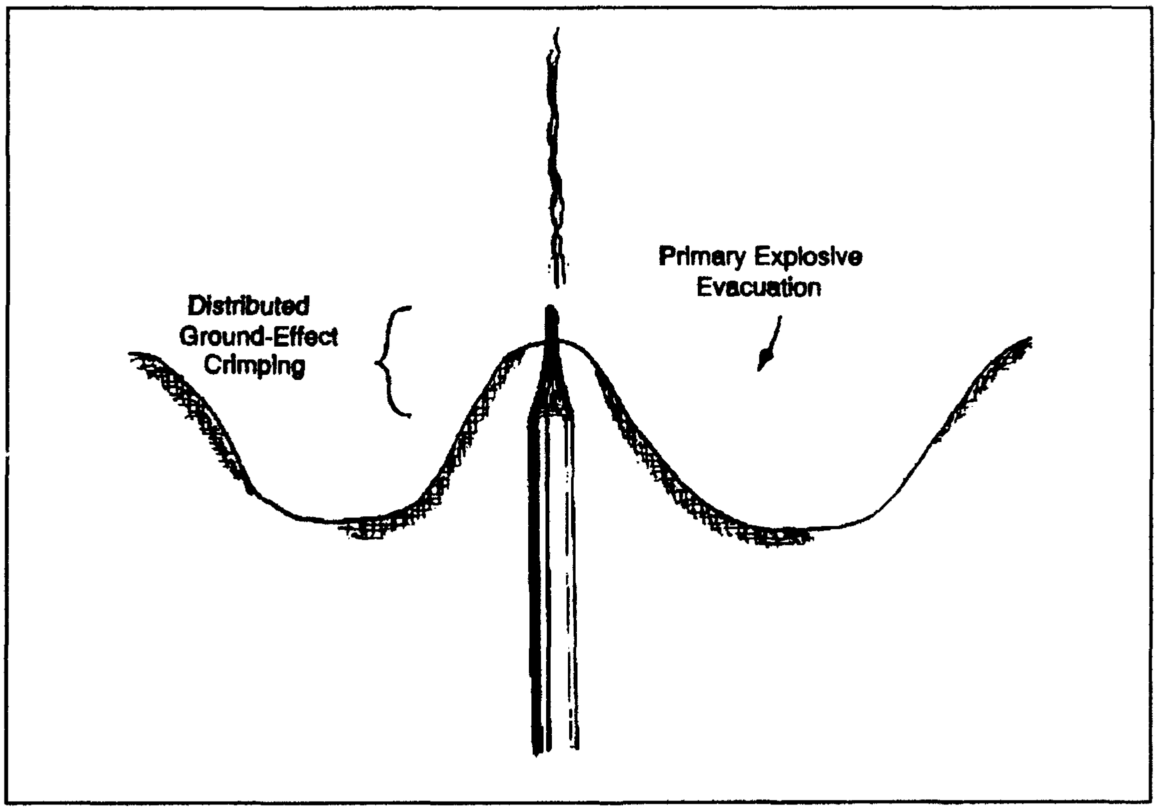

Figure 13. Excavated crater and crimped well stem (C.O.R.T., 1991:Fig 2)

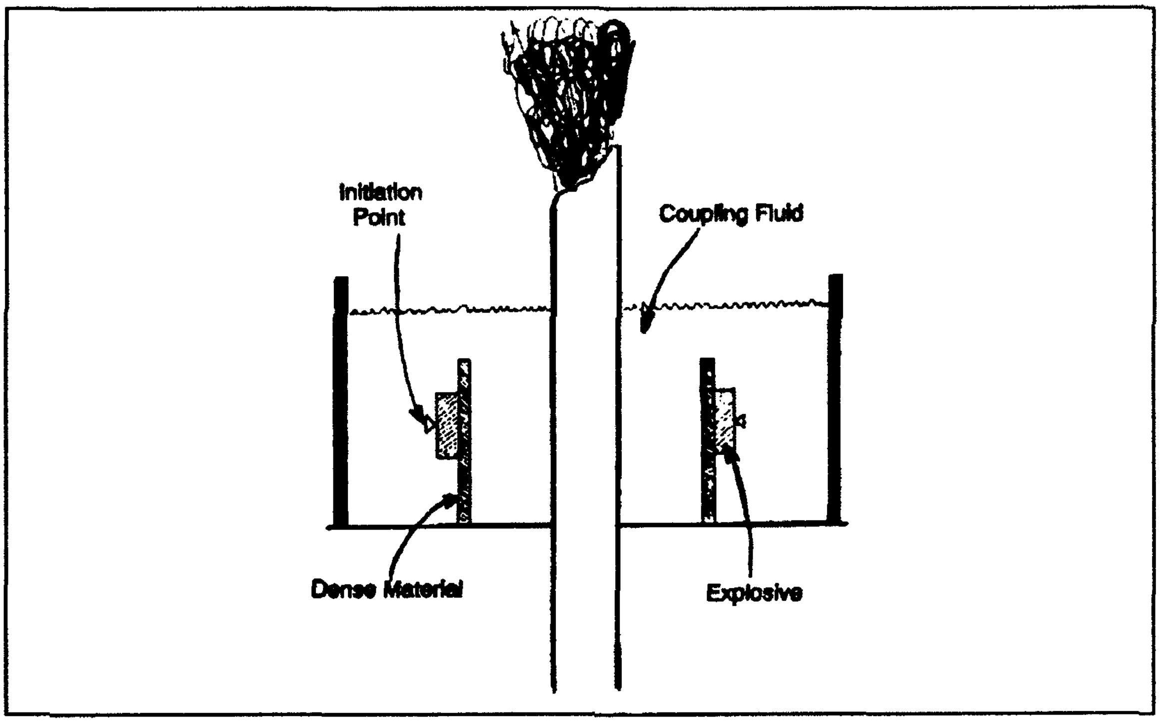

Figure 14. Schematic showing the essential features of the near-field precision crimping charge (C.O.R.T., 1991:Fig 9)

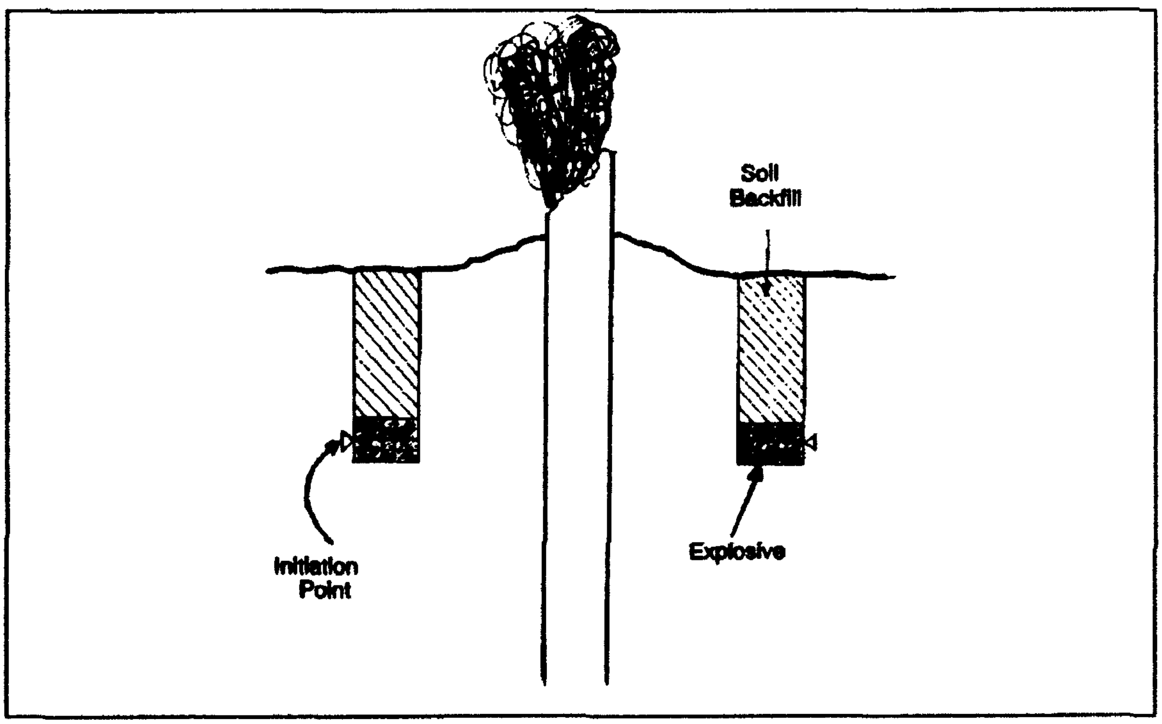

Figure 15. Schematic diagram illustrating the procedure of crimping with buried charges (C.O.R.T., 1991:Fig 5)

The explosives can be placed by air delivery, slant hole drilling or augering, and digging trenches.

Air Delivery. Employment of explosives by air requires the use of precision-guided munitions. One aircraft can deliver one bomb that provides the required crimp. The weapon of choice is the Mk-84, a 2000-pound bomb.

> The suggested means for placing the Mk-84 bomb is by air delivery using . . . precision guidance packages . . . The recommended impact point is at a range of approximately 15 feet from the wellhead, offset by about 3 feet with an impact velocity and fuse delay such as to provide detonation abreast of the well casing. Release conditions for a 97 to 99 percent probability of impact within 15 feet of the illuminated target are: altitude of 17,000 to 20,000 feet above ground, airspeed of 500 [knots true air speed] KTAS or greater, dive angle of 15 degrees or greater. Impact velocity should be 1070 feet per second with a 50 degree angle. (Bretz, 1991a:19)

This would place the weapons at about 10 feet below grade at the time of detonation. A DYNA-2D computer was used to simulate the effects of the detonation on a well casing. The simulation was designed to use the aforementioned Mk-84 criteria. The output plots showing the crimp as it occurs at approximately 0.5-millisecond (ms) intervals are shown in Figures 16,17,18, and 19.

In an actual test at the Shock Physics Division of the Phillips Laboratory at Kirtland AFB NM, a realistic five-ring well casing was constructed and buried in such a way as to replicate an oil well. An Mk-84 was buried and detonated according to the parameters used in the computer model. Following

the test, the pipe was removed from the ground (Figure 20) and sectioned, and a sample was taken from the pipe at the level of weapon detonation. The test achieved complete closure of the production string (Figure 21).

In the Shock Physics Division tests the munition, in addition to crimping the well casing, also excavates the area around the well head. This serves to expose the well casing and allow access that may be necessary for further operations. The use of air-delivered munitions appears to be a viable means to crimp well casings and stop the flow of oil.

<u>Slant Drilling or Augering</u>. Conventional techniques exist that allow technicians to auger holes from a safe standoff distance to a designated depth on either side of the well casing. By using two small explosive charges, crimping occurs without as much longitudinal effect on the well casing as occurs when using one large explosive charge (Tucker, 1991). The effect is similar to "squeezing shut a straw" (Fleck, 1991). The size of the area crimped and the degree of crimp depend on the distance the explosive is from the well casing. Also of significance is the depth at which the charges must be placed. If the ground near the surface is hot enough to induce detonation, then the charges must be placed at greater depths where temperatures are lower (Bretz, 1991b).

Tests were conducted at Kirtland AFB NM using polyvinyl chloride (PVC) pipe and commercial high explosives (Renick, 1991). The explosive of

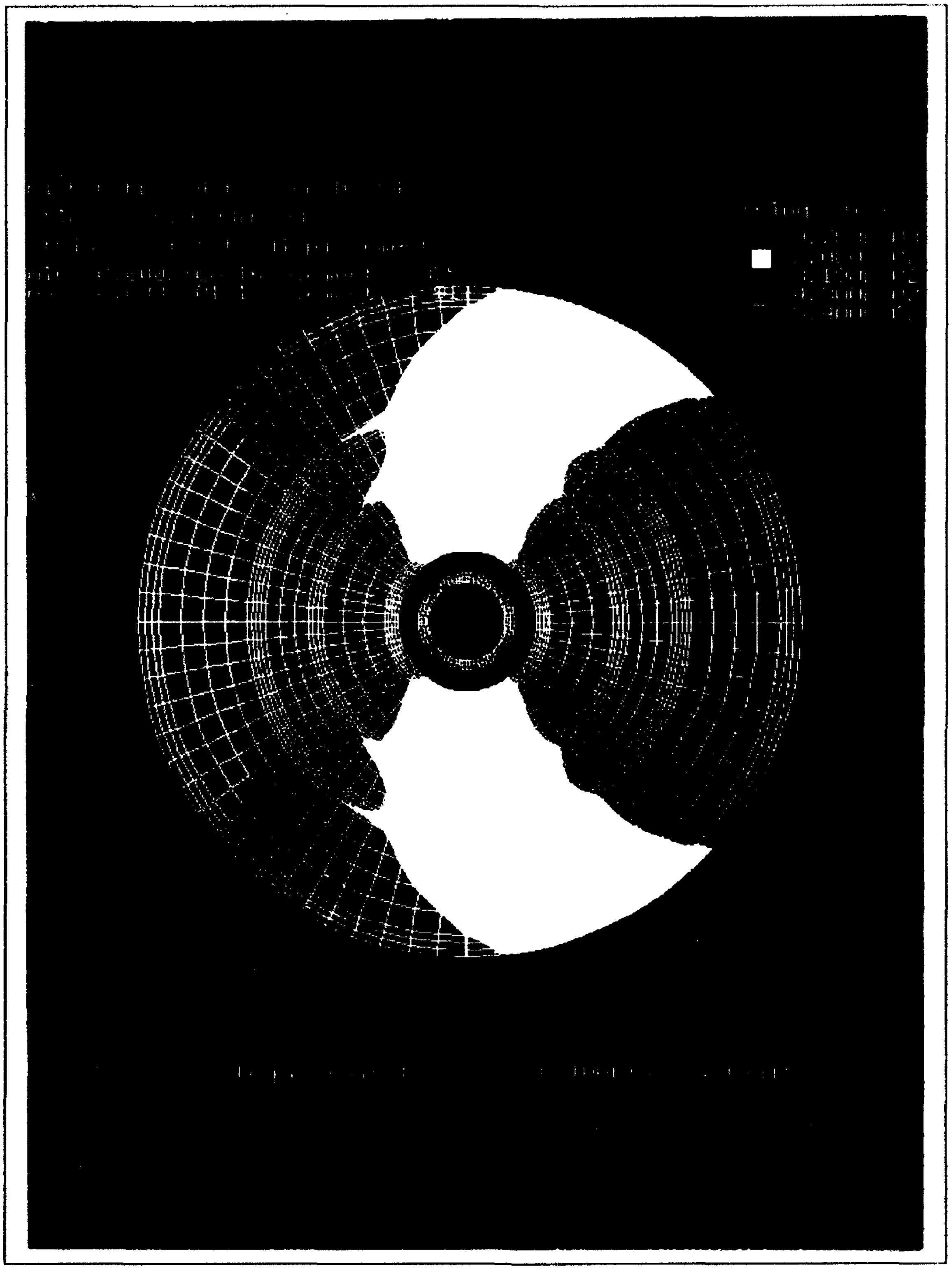

Figure 16. Casing deformation at 1 ms, 1 Mk-84 bomb, 4-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

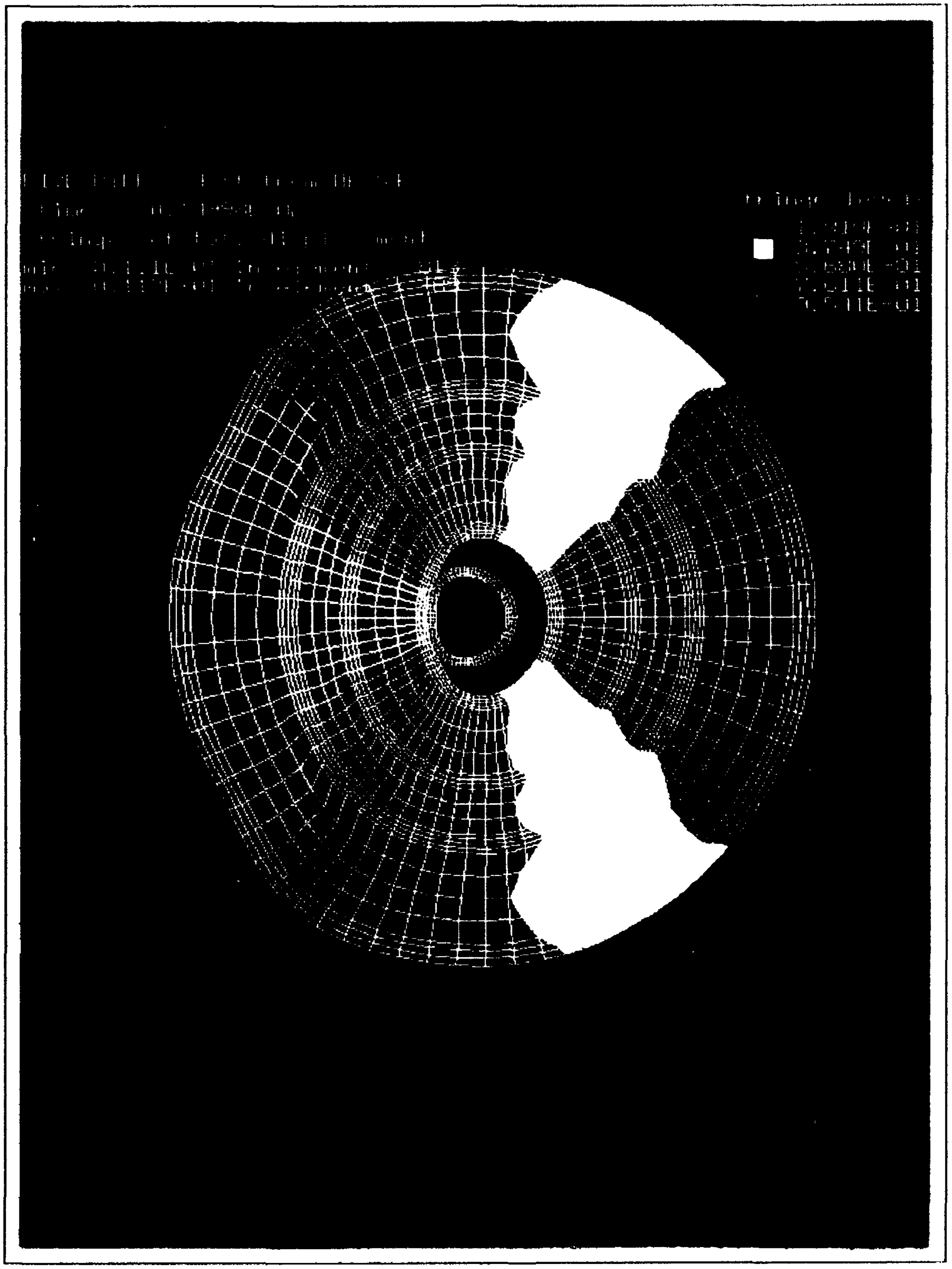

Figure 17. Casing deformation at 1.5 ms, 1 Mk-84 bomb, 4-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

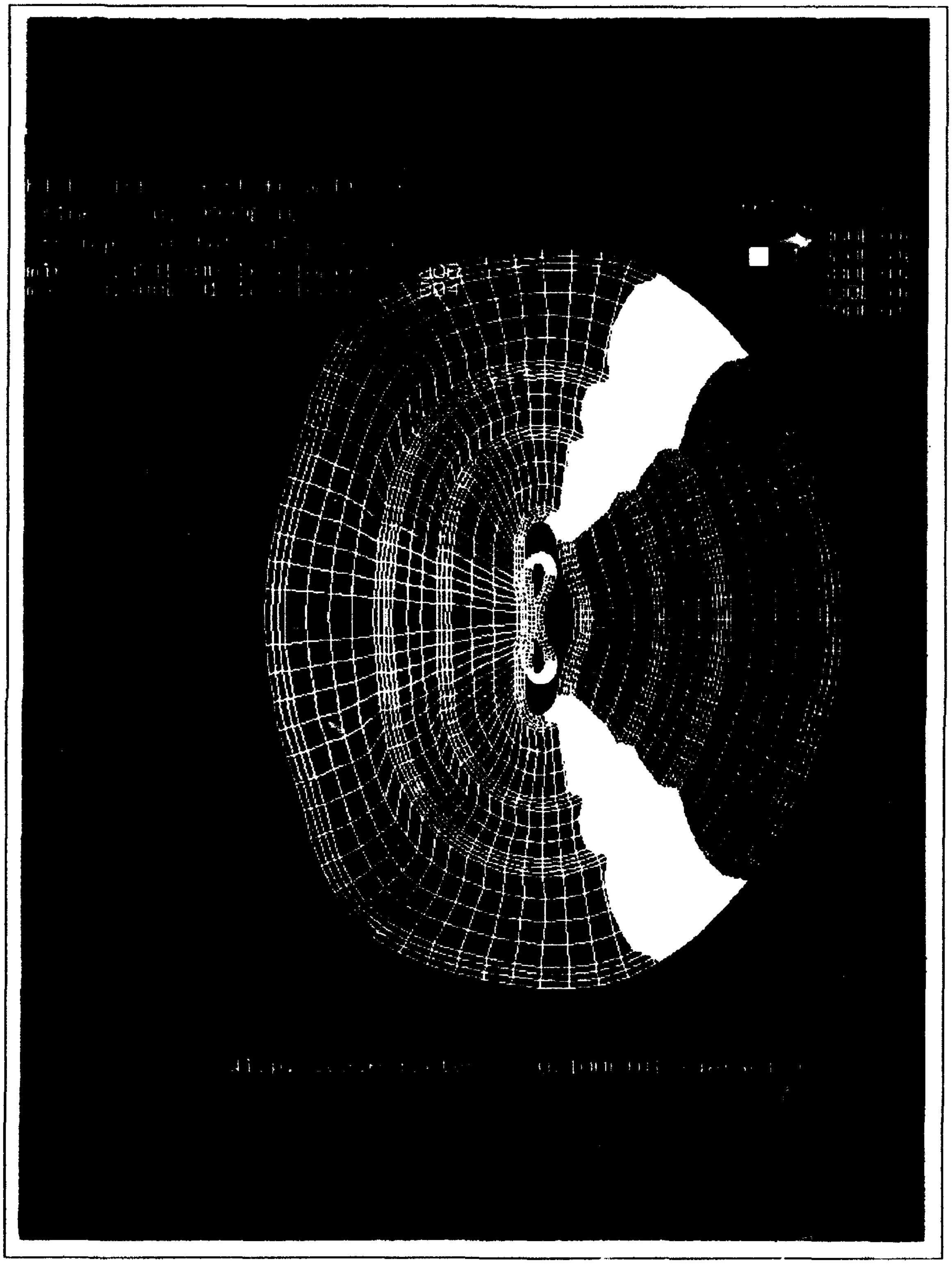

Figure 18. Casing deformation at 2.0 ms, 1 Mk-84 bomb, 4-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

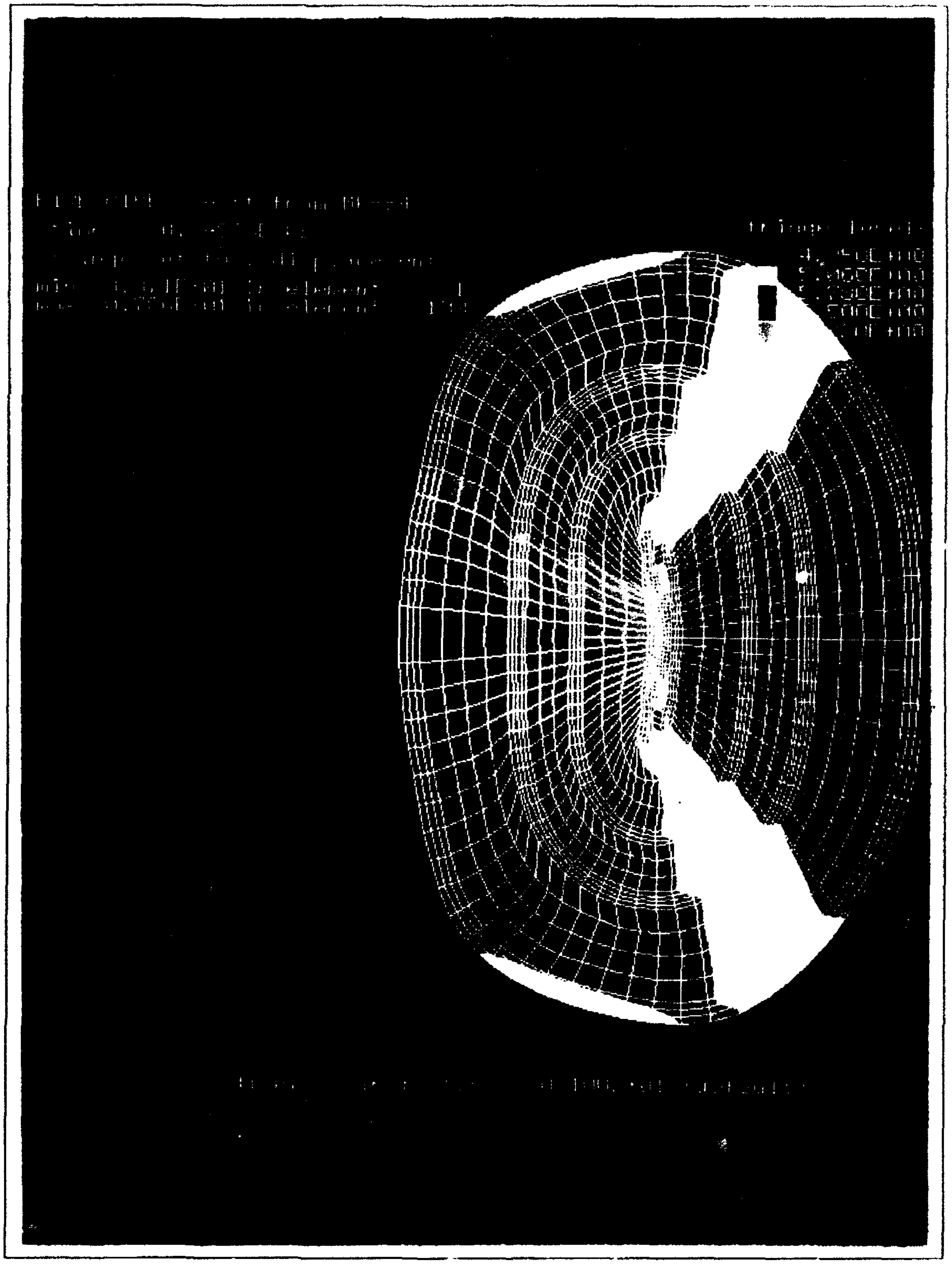

Figure 19. Casing deformation at 2.0 ms, 1 Mk-84 bomb, 4-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

Figure 20. Crimped casing removed from crater following detonation of Mk 84 bomb (Component, 1991)

choice was DBA-105P produced by IRECO Chemicals of Salt Lake City UT. This is an explosive specifically developed for excavation that is "relatively insensitive to thermal and shock effects" (Development, 1991) and is available around the world. It is four times as dense as commercial grade explosives, which allows the diameter of the injection hole in which DBA-105P is used to be half the size required for normal commercial explosives. This reduces costs and drilling time (Development, 1991). This method also results in explosive excavation exposing the well casing for further work.

Figure 21. Crimped casing shown in Figure 20 cut into sections (above) and cross section at closest point to detonation (below)(Component, 1991)

Digging. If a vortex tube is in place, allowing access to the well head, equipment can be used to dig trenches on either side of the well casing in which explosive charges are placed (refer to Figure 15). The trenches are then backfilled, which is important to this application:

> Confinement increases the duration of the explosive event allowing more of the explosive energy to be transferred to the well casing. The increased duration also implies a slower, more controllable crimp. (C.O.R.T., 1991:57)

The Shock Physics Division of Phillips Laboratory did extensive testing of this technique using Mk-82, 500-pound bombs.

> Since Mk-82 bombs were available in Saudi Arabia, . . . [Phillips Laboratory] decided to exploit that availability to avoid the delays associated with developing, producing and transporting specialized explosive charges. (Development, 1991)

At that time the oil well fires were expected to be burning for two to five years and speed was of the essence (Development, 1991).

The test initially involved computer modeling of the event using the DYNA-2D computer simulation. In the test the simulated Mk-82 bombs straddled the well casing at a depth of 8 to 10 feet below grade. The results of the modeling show a successful crimp (Figures 22,23,24).

In the actual test a five-ring well casing was constructed and buried in the ground, and two Mk-82s were simultaneously detonated at three different locations along the casing. Each pair of bombs was placed at a different distance from the casing (Figure 25). The bombs were detonated with tail

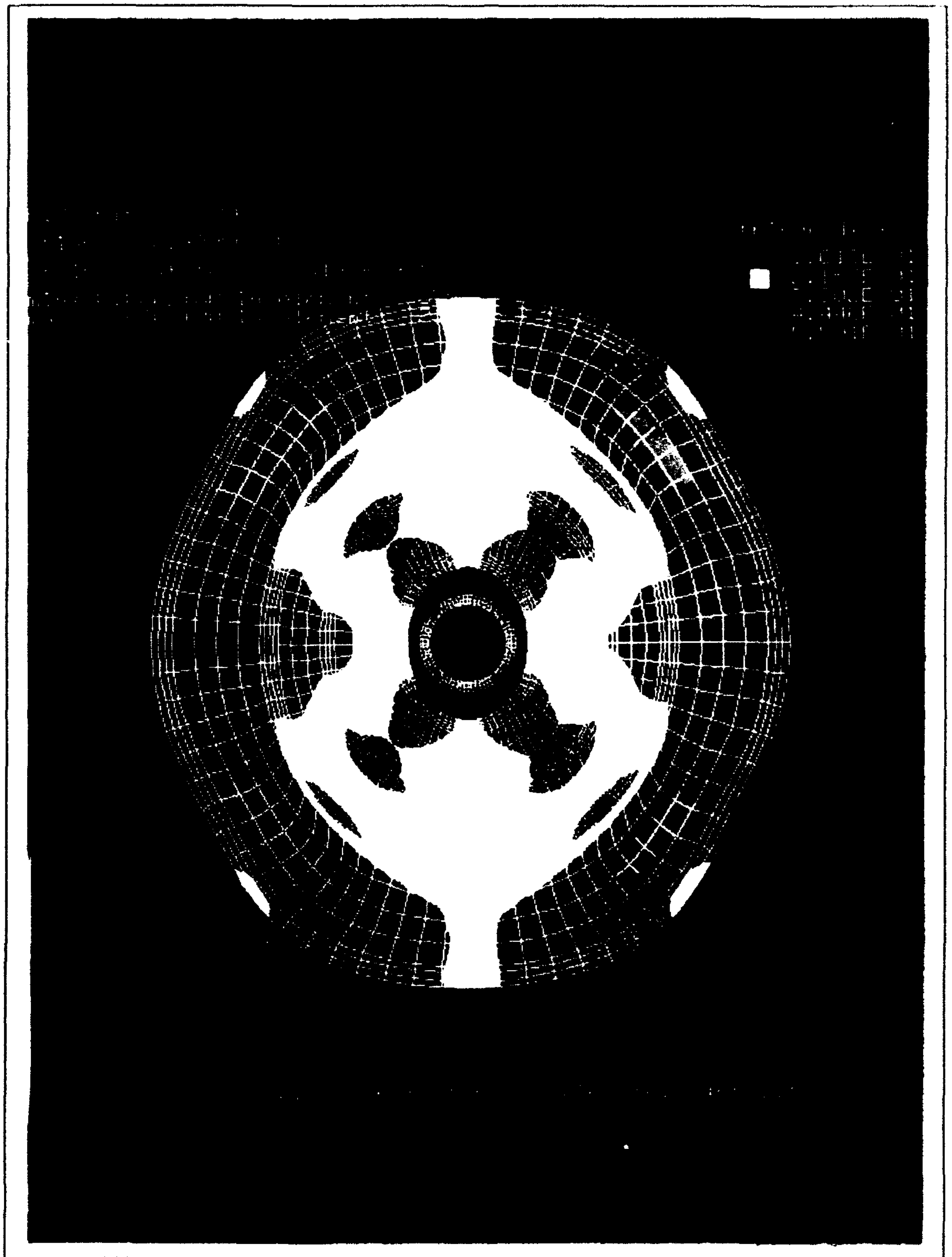

Figure 22. Casing distortion at 0.5 ms, 2 MK-82 bombs, 2-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

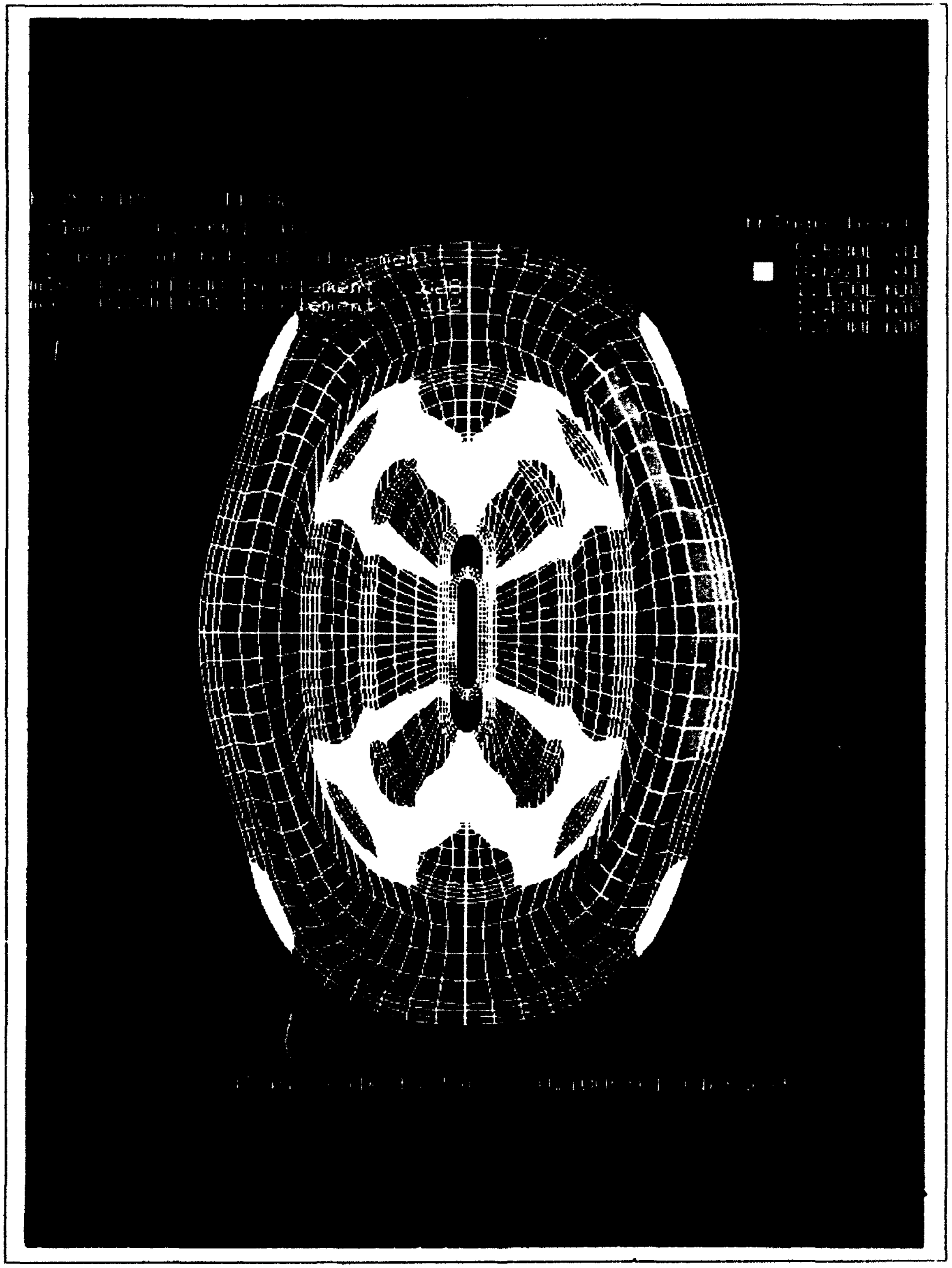

Figure 23. Casing distortion at 1.0 ms, 2 MK-82 bombs, 2-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

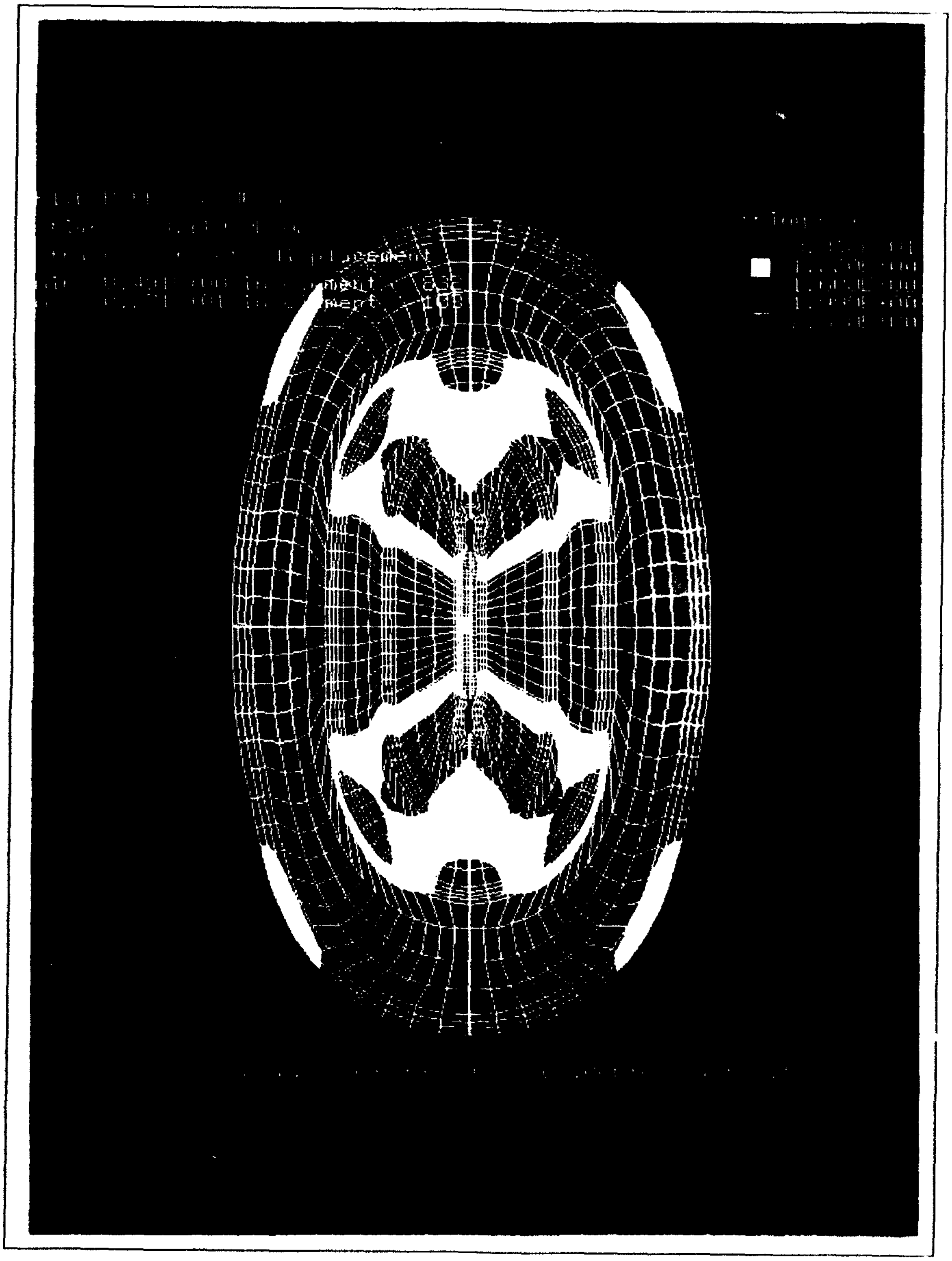

Figure 24. Casing distortion at 1.2 ms, 2 MK-82 bombs, 2-foot separation between well casing and bomb, DYNA-2D calculations (Component, 1991)

Figure 25. Mk-82 500-pound bombs are buried specific distances from a test section of an oil well casing assembly (Component, 1991)

fusing in accordance with the model parameters. Then the pipes were removed from the ground and sectioned. A cross-section (Figure 26), cut from the pipe at the level of detonation, showed complete closure of the production string when the bombs were placed within one foot of the well casing (Bretz, 1991a:20-26).

The report defined "hard crimps" as those in which, "there was complete crushing of all the casings with essentially no open gaps" (Explosive, 1991).

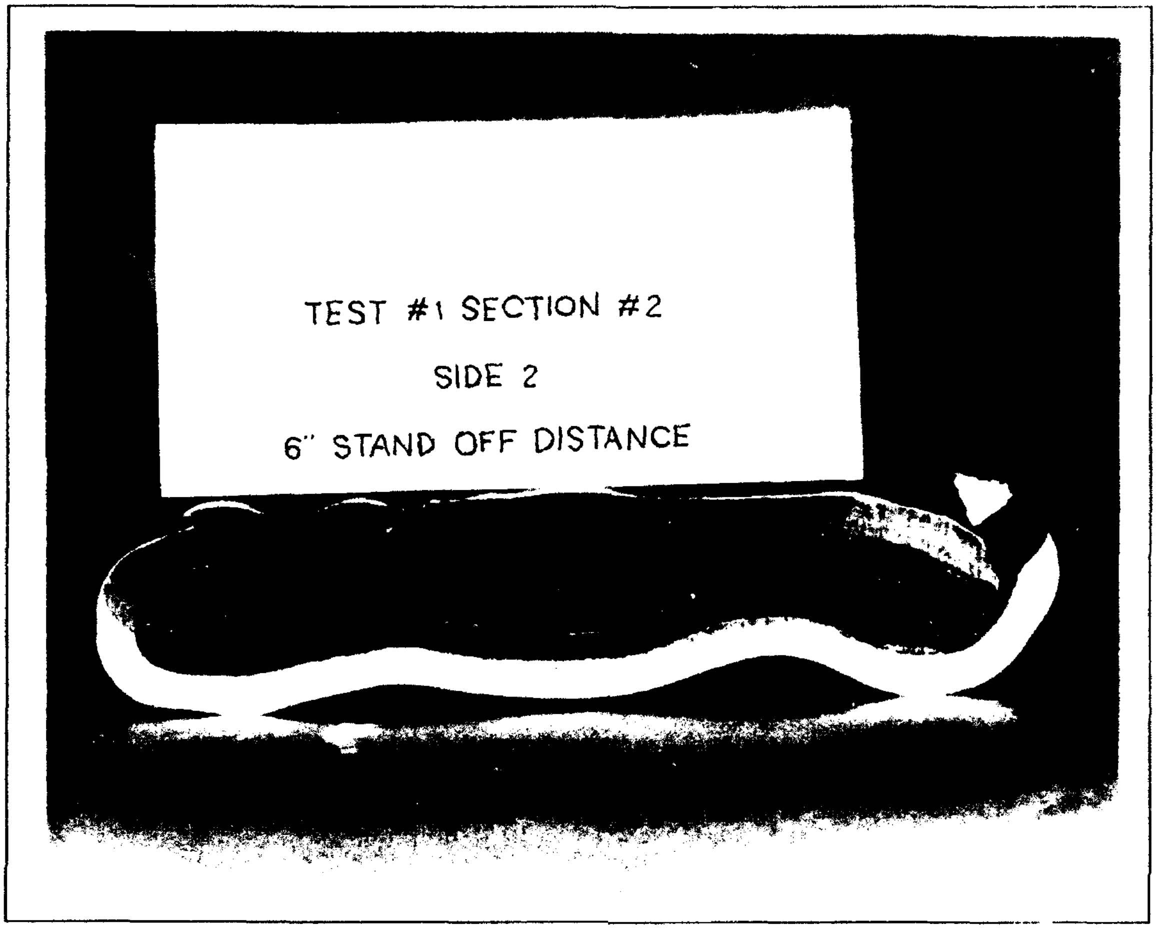

Figure 26. Cross section of oil well casing assembly, taken 6 inches from the point of greatest weapon's effect (Component, 1991)

Soft crimps were those in which the production tube was not fractured and just barely closed, and only some of the other casings were fractured (Explosive, 1991)(Figure 27). Severe fracturing of well casings was characteristic of hard crimps, but was not present in soft crimps. The greater the distance the bombs were from the well casing, the softer the resulting crimp.

Hybrid Methods. A variation of crimping was developed by Exploengineering in Yugoslavia (Petrovic and Duhovnik, 1991).

Figure 27. The top section shows a hard crimp, the lower section is a soft crimp (Component, 1991)

It used the athey wagon boom to lower a valve assembly and oil diverter over the well head once the christmas tree was removed (Figure 28). Two rings of plastic explosives surround the lower orifice of the assembly (Figure 29). When the charges were detonated, the lower portion of the assembly was compressed around the external well casing, attaching the assembly to the well head.

Once this assembly is attached to the well head, a stinger is inserted down into the oil flowing through the center of the assembly (Figure 30). It is then pressed into the production string to a depth of up to 15 meters. Inside the

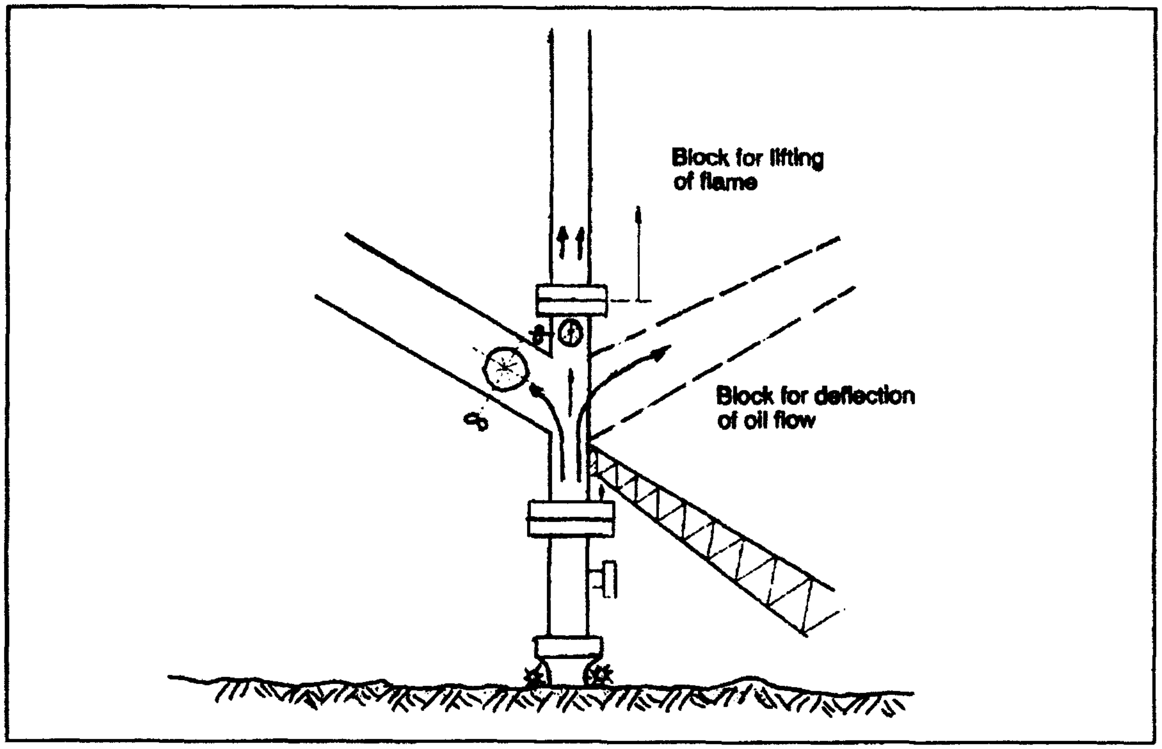

Figure 28. Multipurpose pipe for extinguishing oil wells by outside explosive charge (Petrovic, 1991:6)

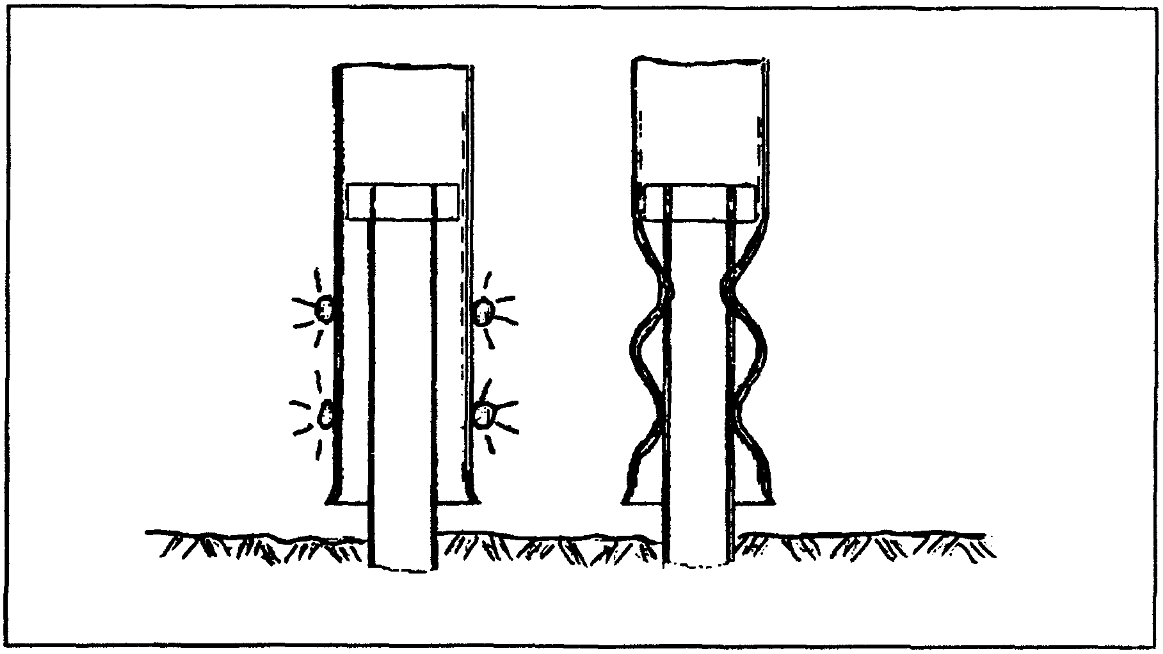

Figure 29. Tube in place over well head and the plastic explosive charges are detonated (Petrovic, 1991:7).

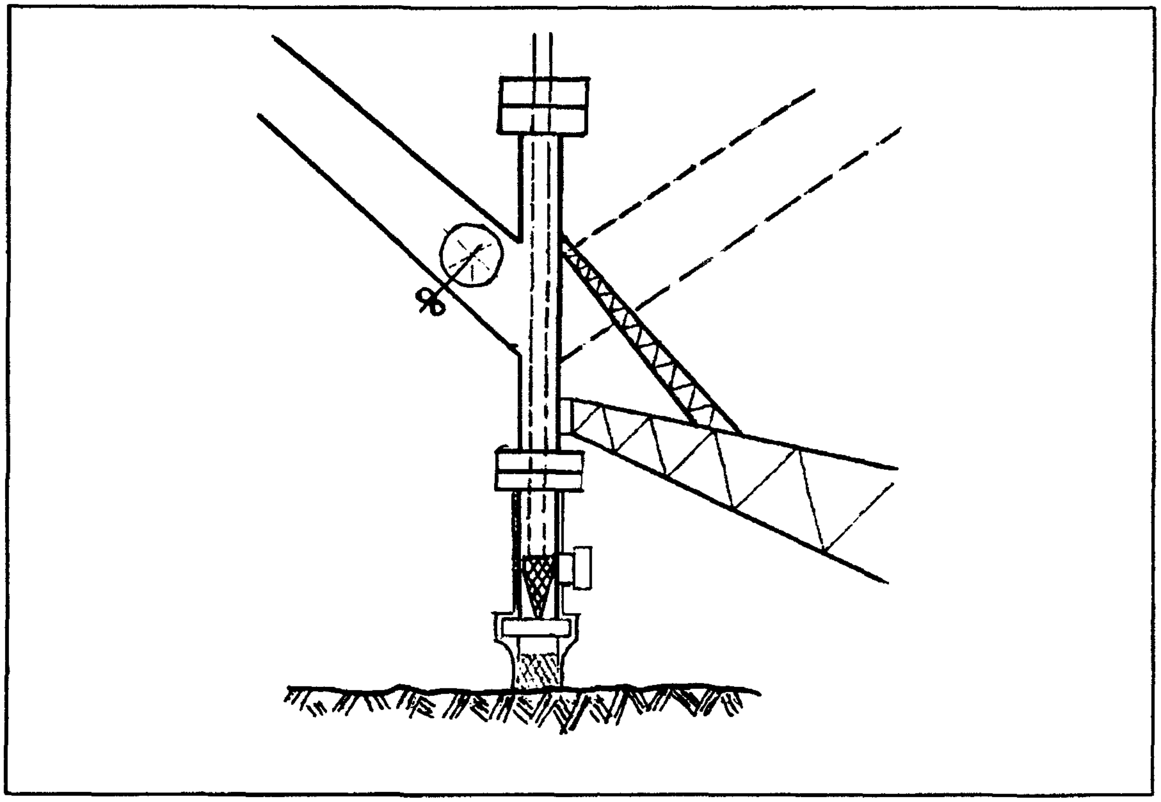

Figure 30. Stinger is inserted through oil flow and pipe assembly (Petrovic, 1991:9)

nose of the stinger is a series of explosive charges. Once the stinger is well into the production string, the charges are detonated in stages. This forms a wedge that expands the stinger in the string, firmly holding it in place (Figure 31). The petroleate flow continues through the stinger which has a valve assembly allowing the flow of oil and gas to be shut off or reopened at will.

The concern that focused attention on other methods of crimping was the need to safely control the detonation to shut off the flow of oil without damaging the well head. This concern generated methodologies that did not require explosives.

Mechanical Devices. Battelle-Frankfurt, the Germany based division of Battelle International, developed a variation of a technology used in Germany to seal high-pressure gas pipes and adapted it for use on burning oil wells (Blowout, 1991). The technology is basically the same for use either above surface or below grade.

> The Battelle module has hydraulically driven pistons located inside a pressure-tight chamber mounted around the production casing. Production casing and production tubing are simultaneously squeezed together by specially formed pistons which stop the oil flow in the production tubing as well as in the production casing. The production casing is completely jacketed by the pressure-tight chamber around the squeezing area. (Blowout, 1991:1)

The hydraulic pistons apply a force of 800 tons and once employed can be mechanically arrested so the hydraulic equipment can be removed (Figure 32). This is especially important when working space is at a premium as it is in underground tunnel applications (Blowout, 1991:7).

When the Battelle module is used above grade, protection from heat is required. This could come with the use of a vortex tube and heat shield or some similar device. The area surrounding the well head is then excavated and all the outer casings, except the production casing, are removed (Figure 33). The production casing is sandblasted clean to permit a tight fit of the sealing collars of the pressure chamber. The pressure chamber assembly is then mounted to the production casing (Figure 34), and specially-shaped hydraulic pistons are actuated, stopping the flow of oil and gas. A blowout preventer,

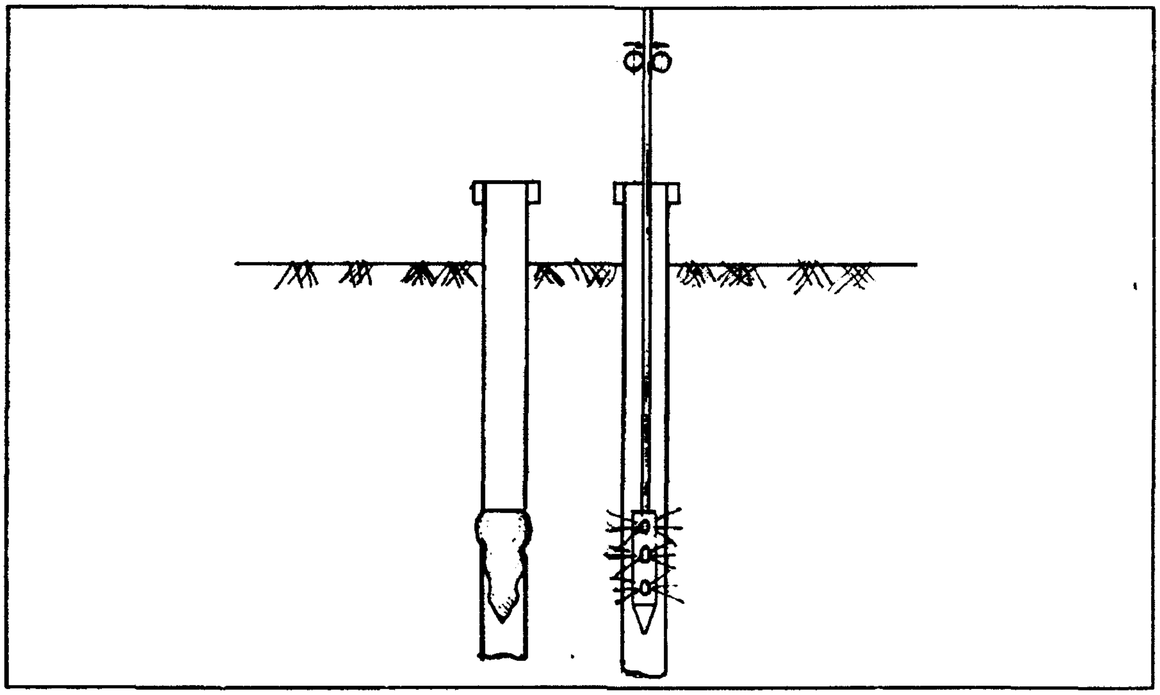

Figure 31. Explosives in the head of the stinger are detonated once it is inserted into the production string (Petrovic, 1991:11)

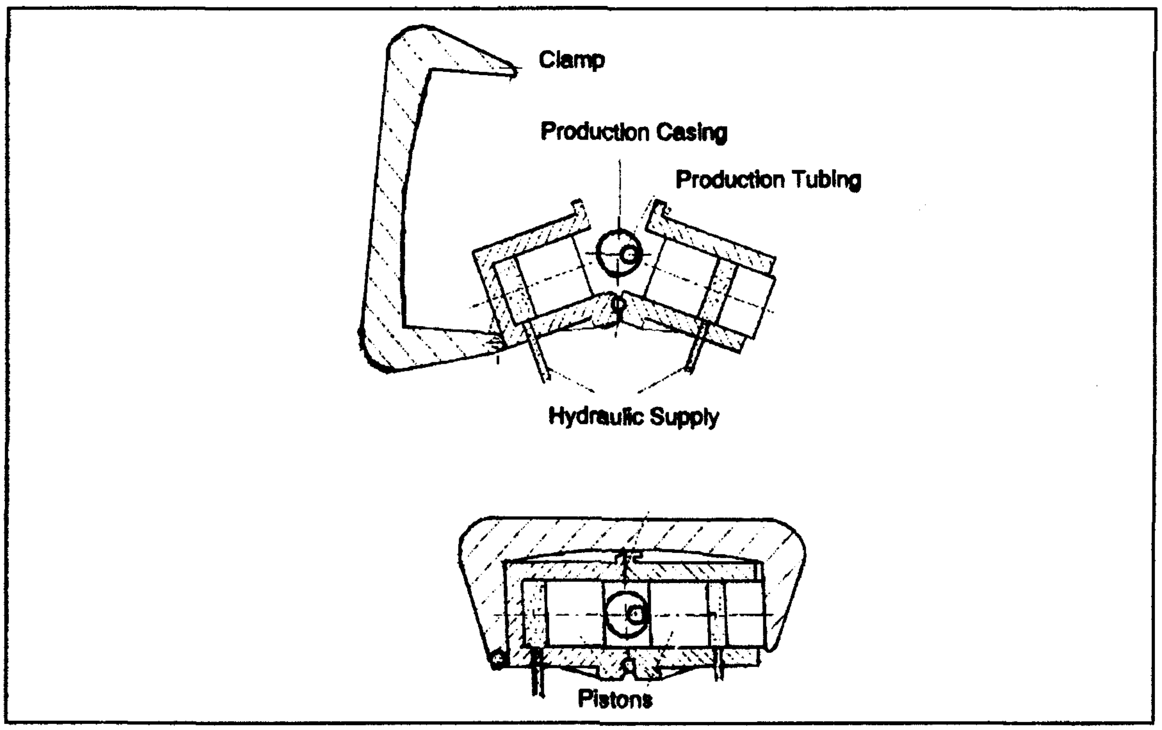

Figure 32. The Battelle pressure chamber with hydraulic pistons (Blowout, 1991:Figure 1)

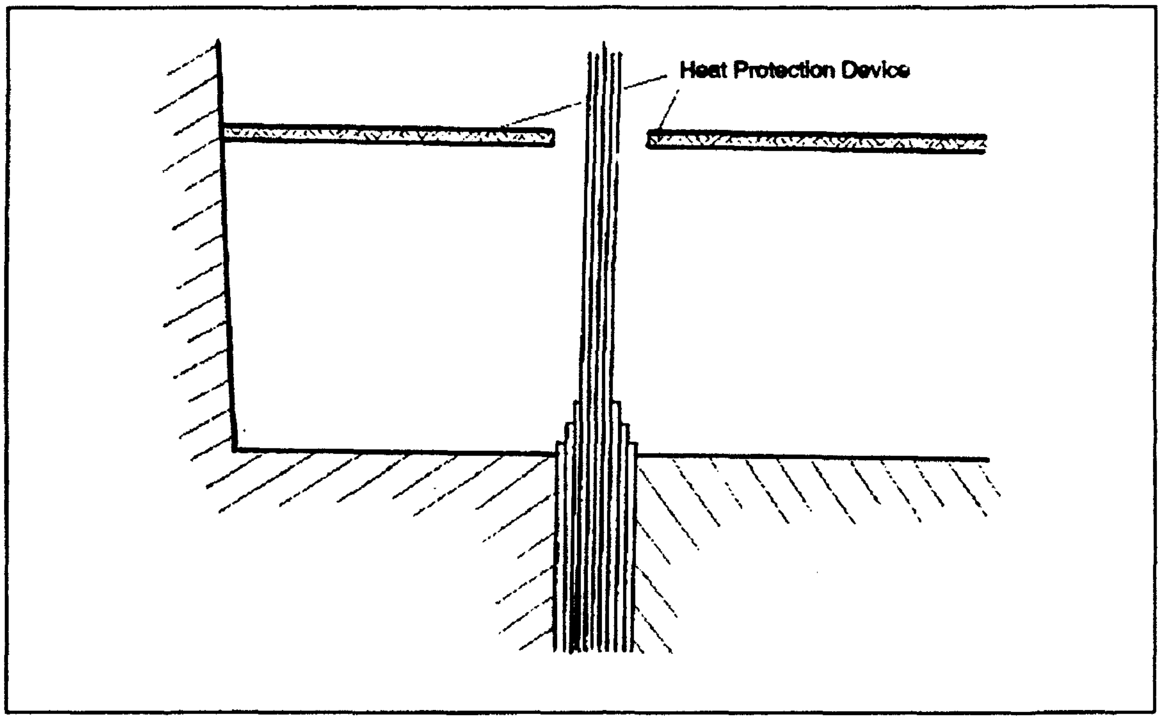

Figure 33. The casings are removed down to production casing which is cleaned by sandblasting (Blowout, 1991:Figure 1)

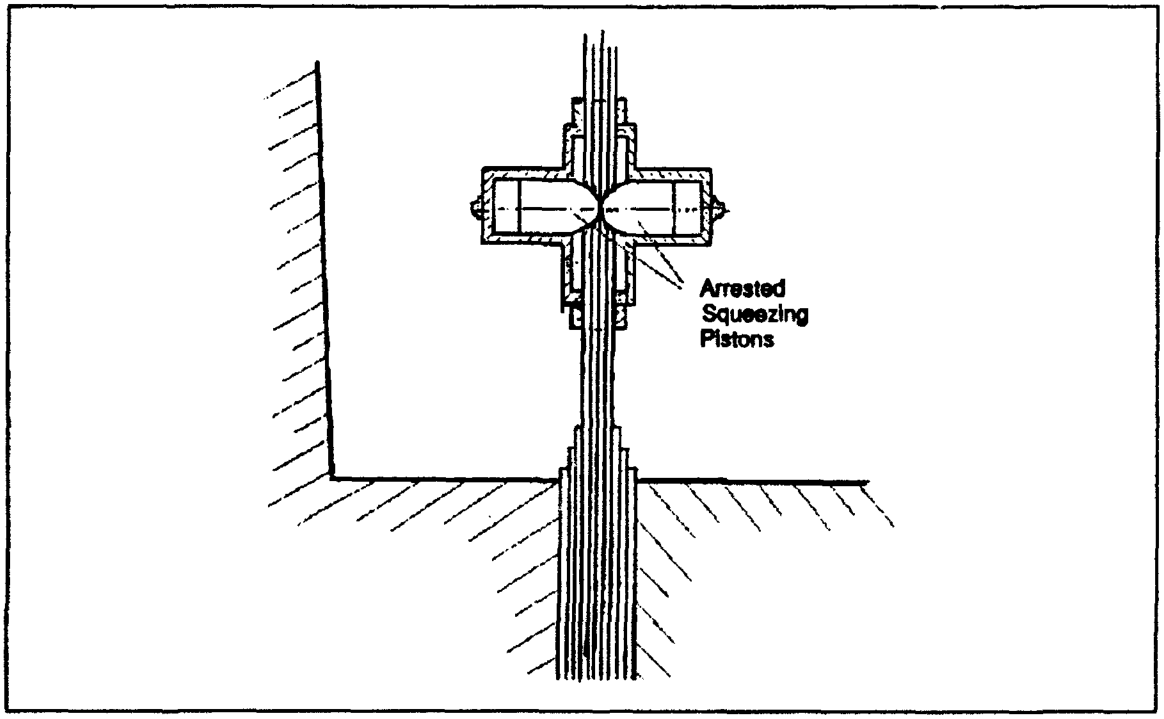

Figure 34. The pressure chamber in place and pistons activated (Blowout, 1991:Figure 1)

which is a system of safety valves, is then mounted on the production casing, and the pistons are released. A hole is then drilled through the crimped pipe section via the preventer; a tube is installed; and the well is killed with the appropriate muds (Blowout, 1991:4-5).

If the cellar cannot be excavated, if no heat deflecting equipment is available, or if there is insufficient water to cool the area around the damaged well casing, underground procedures can be employed (Blowout, 1991:3). These procedures require a tunnel be excavated to the well casing and sufficient working area be excavated around the casing to allow the employment of the pressure chamber (Figure 35). Again, the cement and outer casings are stripped to expose the production tube. In this situation each of the casings must be supported. The pressure chamber is attached, and the pistons are activated as before resulting in a crimp that stops the flow of oil (Blowout, 1991:4-6).

Crimping, as a technology, received an abundance of research in the proposals submitted to KPC. It has been proven successful at stopping the flow of oil and gas in varying degrees, depending on the particular methodology applied.

Analysis of Crimping Technologies

High Explosives. The use of high explosives is not new to the military. Qualified personnel and training curricula exist to develop these skills.

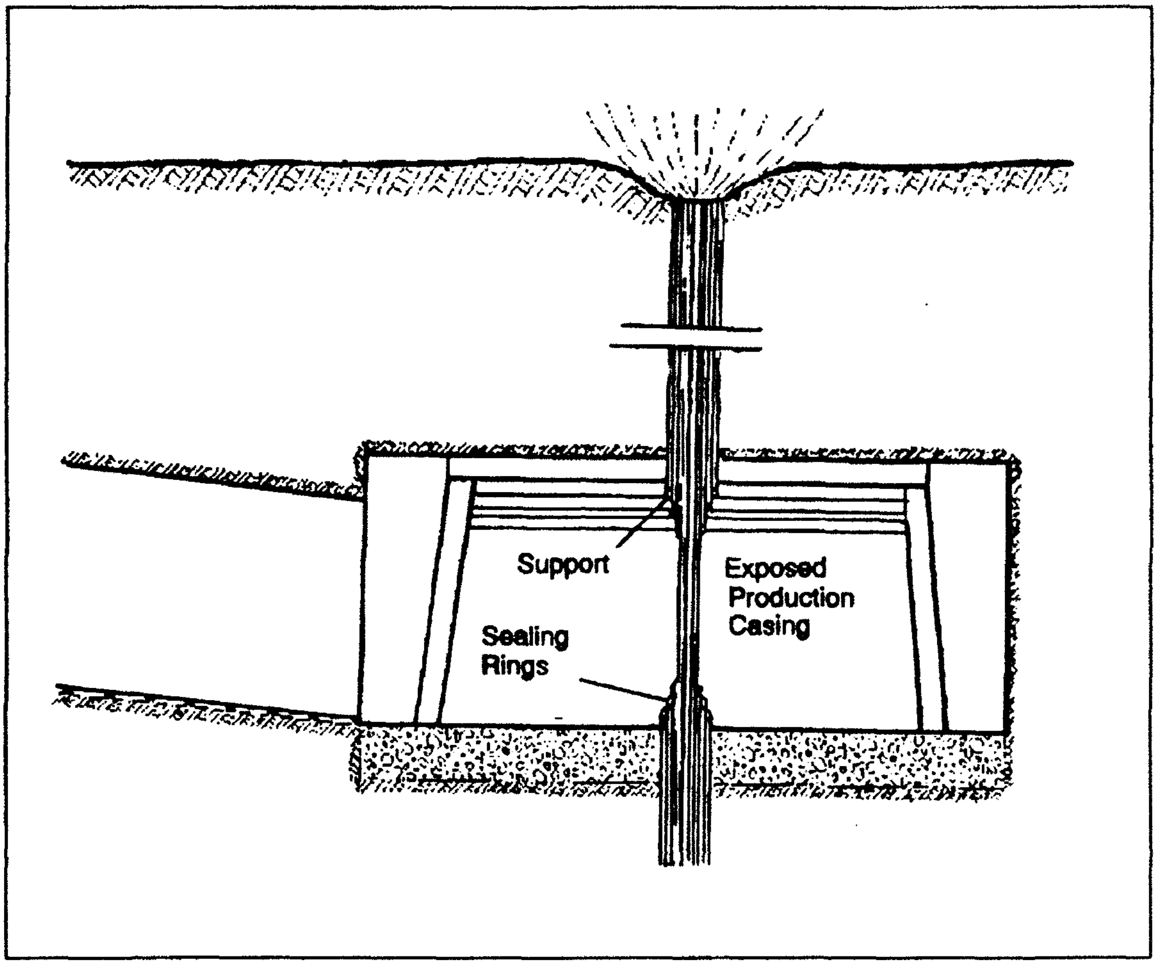

Figure 35. Tunneling provided access to well casings which are stripped down to the production casing (Blowout, 1991:Figure 1)

Also, explosives produced to exacting military specifications are stockpiled and readily available.

An explanation of the analysis, by criterion, is included next. In all cases, the criteria referenced are those developed in Chapter III.

Surface Detonations. The Stewart proposal suggests crimping using small explosive charges once the area has been cleaned, christmas tree removed, and vortex tube placed.

1. The technology is able to eliminate the smoke by shutting off the flow of oil feeding the fire.

2. The research and development (R&D) has been accomplished, but the method has not been field tested.

3. There are military schools that teach the skills necessary to accomplish the explosives tasks. The skills that are not taught are those required to clear the area, remove the christmas tree, and install the vortex tube.

4. The equipment necessary to apply the explosive charges, including the explosives, is in the military inventory.

5. The equipment outlined in the proposal appears to be suited to the rigors of the oil fields and able to operate in the demanding environment.

6. The equipment required to implement *this methodology is sized* to allow transport in military aircraft.

7. Once the well head area access is provided, this method can be implemented in a matter of hours.

8. The support equipment required to perform the tasks necessary to access the well, such as the athey wagon, vortex tube, and cooling equipment, is not in the military inventory and must be purchased commercially.

9. This methodology does not keep workers at a safe distance. This is because it requires well head access using equipment and labor not within military inventories.

In subsequent analyses the criteria will be addressed by exception. Methodologies that do not meet the criteria will be discussed along with comments if appropriate. However, positive characteristics that are especially appealing may be described also. A comprehensive table summarizing the results of the analysis will be presented in Chapter V.

The HYDROCUT proposal is unique in that it is one of the few methods presenting a capability to directly access the area around the well head without any preparatory work or preliminary cooling. The major drawback to the HYDROCUT proposal is its requirement for substantial time and money investment in R&D and fielding of both primary and support equipment. None of the equipment or skills are currently used by the military. All other crite ia are met.

Sub-surface Detonation. The explosives can be employed in three ways; (1) from the air, (2) staying a safe distance from the well and drilling a slant hole to the well casing, or (3) digging trenches next to the well casing and burying the explosives.

Air Delivery. This methodology meets all primary criteria. However, noncompliance with ancillary criteria is a concern. Accuracy is required to minimize damage to the well casings. Depending on the proximity of the bomb to the well casing when detonated, significant damage to the cellar and well casings could result.

"A big advantage of air-delivery is that no access to the wellhead is required" (Bretz, 1991a:19). Another advantage is the speed with which it can be employed. The disadvantage of air delivery is the very thing making it necessary, that is "laser designation is seriously affected by particulates and thermal-induced turbulence" (Bretz, 1991a:19). As such, the pilot would have to approach the burning well from upwind. If there were no appreciable winds, smoke could obscure the target to the point that a special reflector might have to be placed at the aimpoint and designated by a ground unit (Bretz, 1991a:19).

Slant Drilling or Augering. All but three criteria are met by using this technology. Sufficient tests were conducted by researchers at the Kirtland AFB NM Shock Physics Division to prove its viability in crimping well casings. The use of slant drilling and augering equipment is not taught in military training centers, and the equipment is not in the military inventory. A drawback of this method is the standoff distance required to escape the heat of the burning well. Cooling systems to support this methodology would reduce this distance significantly. The greater the required standoff distance the more time required to bore the required holes. The extensive standoff distances required to operate in the heat of the well increase employment times to the point of violating the requirement for rapid employability.

Digging. The Shock Physics Division initially indicated, based on abundant data, that renewed research and development were

not necessary for developing the methodology (Bretz, 1991a). They reported that this methodology was able to be fielded immediately. The skills to dig the trenches and employ the explosives or munitions are available in the military. Although using the Mk-82s to crimp the well casing appears to be viable, a Phillips Laboratory report points out that the bombs are not the preferred explosive (Development, 1991).

> Time permitting, it is highly advantageous to develop the specialized charge which . . . are expect[ed] to be inexpensive and easier to handle in the field [than Mk-82 and Mk-84 munitions]. (Development, 1991)

This suggests that further research may prove the use of this technology even more effective.

This technology requires access to the well casing to dig the trenches. Operations require conventional oil well firefighting skills and the use of the specialized support equipment used in applying conventional technologies. The support equipment includes an athey wagon, vortex tube, and all the apparatus necessary to provide water for cooling the area. The equipment is not in the military inventory.

<u>Hybrid Methods</u>. The hybrid methods proposed by Exploengineering, though already fielded, would require modification and redesign to be compatible with U.S. equipment. The training and equipment to employ this technology are not currently available in the military. This methodology requires support equipment such as an athey wagon. It also

requires the capability to remove the christmas tree and excavate the area around the well head. This process requires substantial quantities of water and pumping equipment for cooling the area around the well head. Considering their current levels of training and equipage, the application of these skills and equipment requires military personnel to work dangerously close to the burning well.

Mechanical Devices. The Battelle-Frankfurt pressure chamber with hydraulic pistons may well be an effective means of crimping as it meets many of the established criteria. The most significant problem is that it requires technicians to have either access to the well casing on the surface or have the capability of tunnelling to gain access, in order to work safely away from the heat. The support equipment to provide either means of access is not available in the military inventory. Further, once access is achieved, the well casings must be tested for annulus pressure and leakage, and then removed one at a time until the production casing is reached. If this is done in a tunnel, all of the outer casings must be supported as well. The training and the support equipment needed to employ this technology are not in the military inventory either.

In addition to crimping, other technologies are available to extinguish the flames of a burning oil well. The next technology discussed is the application of chemicals to the burning well head and surrounding area.

Description of Chemical Application Technologies.

The essence of this technology is the application of chemical agents onto or into the oil well fire. The agents remove the heat or chemically react to produce gases that displace the oxygen (Buxton, 1991). The particular agent used dictates the amount of the chemical required and the amount of water, if any, required to cool the area surrounding the well head to prevent reignition of the fire. The amount of wind determines the stand time or dispersion of the agent which in turn affects both the agent's ability to cool the area and the amount required to extinguish the fire. Before discussing the various means of applying the agents, attention is focused on the agents themselves.

Chemical Agents. The first research in this area concentrated on the use of halons which "are low boiling point liquids or gaseous halogenated hydrocarbon (halocarbon) fire extinguishing agents" (Tapscott, 1991).

> Halons do not act by smothering; instead, they remove the highly reactive "free-radical" molecules formed in fires which maintain combustion. Thus, halons strike at the fundamental chemical reactions that cause burning. (Floden, 1991:13)

"Halons can extinguish fires at concentrations well below five percent because they have two modes of extinguishment - physical and chemical" (Tapscott, 1991). As such, halon is quite effective as a firefighting agent, but unfortunately it has serious ozone depleting properties. The U.S. agreed to phase out the country's production and use of halon, and was a signator of the international treaty known as the Montreal Protocol which increasingly restricts

the use of halons and bans their use by the year 2000 (Tapscott, 1992). Although halon is a superb firefighting agent, substitutes must be developed for use. According to Dr. Robert Tapscott, a member of the Montreal Accords Committee, substitutes for halon are called either replacements or alternatives. Halon replacements are clean and halon-like, leaving little or no residue and requiring minor and often no cleanup. In contrast, halon alternatives are dirty and not halon-like, leaving scum or a crusty film that often requires a significant cleanup effort. Neither replacements nor alternatives extinguish fires as effectively as halon, but in firefighting of this nature, either may work satisfactorily (Tapscott, 1992).

Another highly effective extinguishing agent is potassium bicarbonate, often known as PKP. It and sodium bicarbonates ($NaHCO_3$) are generally used for oil type fires and Mono Ammonium Phosphates ($(NH_4)_2PO_4$, $(NH_4)H_2PO_4$, $(NH_4)_3PO_4$, $(NH_4)SO_4$) for gaseous fires. A mix of the two powders would be effective against oil and gas fires, depending on the mix of the oil and gas (Buxton, 1991:3).

HBFC-22B1 (CHF_2Br) is sold by Great Lakes Chemical under the trade name Fire Master 100. It is one third to one tenth as high an ozone depleter as halon (Tapscott, 1992).

124B1 is produced by Imperial Chemical Industries of Great Britain. Its ozone depleting potential is higher than the U.S. Clean Air Act allows.

Perflorohexane (C_6F_{14}) is not considered an ozone depleter and is virtually nontoxic. It is produced by the 3M Corporation but has not yet been approved by the U.S. Environmental Protection Agency (USEPA) for use in the U.S. as a firefighting agent. One third more of it is required than is required to accomplish the same firefighting task using halon (Tappscott, 1992).

HCFC-123 (CF_3Cl_2) has the same fire extinguishing capabilities as perflorohexane. It was developed by the New Mexico Engineering Research Institute (NMERI) as a fire extinguishing agent, but it is sold by Dupont Corporation as a refrigerant. It is advertised as a firefighting agent called FE-232 but has not been approved for use by the USEPA (Tappscott, 1992).

Halotron, a halon replacement, was developed by the Swedish company Halotron Inc. and is marketed for other than firefighting purposes by American Pacific Chemicals. Its properties are similar to HCFC-123 (Tapscott, 1992).

Dry-ice was recommended to KPC, but it is not feasible because it does not have sufficient heat absorbing capability. As a result, an infeasible amount of dry-ice is required to achieve satisfactory cooling.

The means of delivery of these chemicals vary but can be broadly categorized into four methods of employment. The agent can be delivered in a bomb dropped from an aircraft, inserted into the flame, streamed into the flame, or ground launched by a cannon or rocket launcher.

Air Delivered Agents. This concept, developed at the Shock Physics Division of the Phillips Laboratory, involves replacing the chemical agents in chemical delivery bombs with fire extinguishing agents. The bombs could then be delivered by conventional strike aircraft. Because of the capacity of each bomb and the amount of agent needed, more than one bomb is required. The delivery is complicated because near-simultaneous detonation of all bombs is required to achieve the desired effect.

> The munition thought to be readily available and most workable for this situation is the 500 pound Mk-116 (WETEYE). An alternative is the 500 pound Mk-94. The bombs should be fused with proximity fuses set to detonate two or three feet above the base of the flame. The burster tube in each munition would then explode, rupturing the case, and create a cloud of liquid/vapor . . . much like a fuel air explosive (FAE) cloud. (Bretz, 1991c)

Air delivery of agents has been investigated at Kirtland AFB NM as well as Eglin and Tyndall Air Force Bases in Florida.

Mechanically Inserted Agents. This approach assumes that equipment inserted into the flames immediately over the well head will inject the agent into the flames. One proposal was designed specifically for the Kuwaiti oil well firefighting effort by Blaze Busters Inc., a consortium of U.S. companies (Project, 1991). The delivery device is mounted on the end of an athey wagon boom and lowered over the well head (Figure 36). A combination of dry chemicals and a delivery catalyst that is "non-toxic and not harmful to the environment" (Project, 1991) is injected through the delivery device. The

delivery catalyst serves to transport the chemicals through the flames. The fire is extinguished by "virtual instant energy absorption" (Project, 1991), removing the heat required for combustion. The consortium maintains that the process itself requires no water as the combination of agents provides the required cooling; however, "in certain cases, limited amounts of water may be required for surface cooling purposes" (Project, 1991).

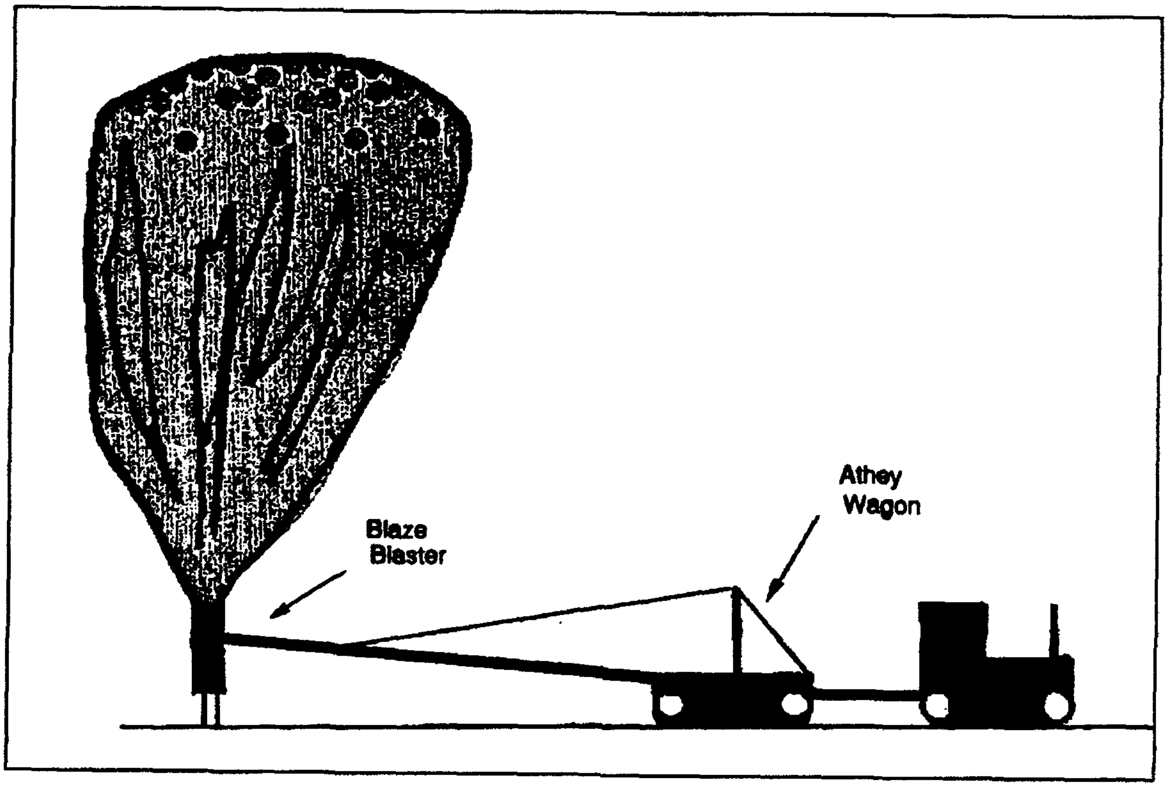

Figure 36. Dry chemicals and a catalyst are injected through Blaze Blaster once it is in place over the well head (Project, 1991)

Streamed Agents. Empire Armor of Sussex, England, recommended a system tested at Louisiana State University and fielded in 1988. The concept involves a two-pronged approach. The area around the well head

is cooled by a dispenser of nitrogen and an undisclosed dry chemical powder mounted an athey wagon boom (Figure 37). The cooling takes less than ten minutes after which a fire control stack (Figure 38), also mounted on a boom, is placed over the burning well head. Dry chemicals are injected at the top of the stack, and nitrogen is injected at various levels within the stack. Together these streams extinguish the fire in seconds (World, 1991).

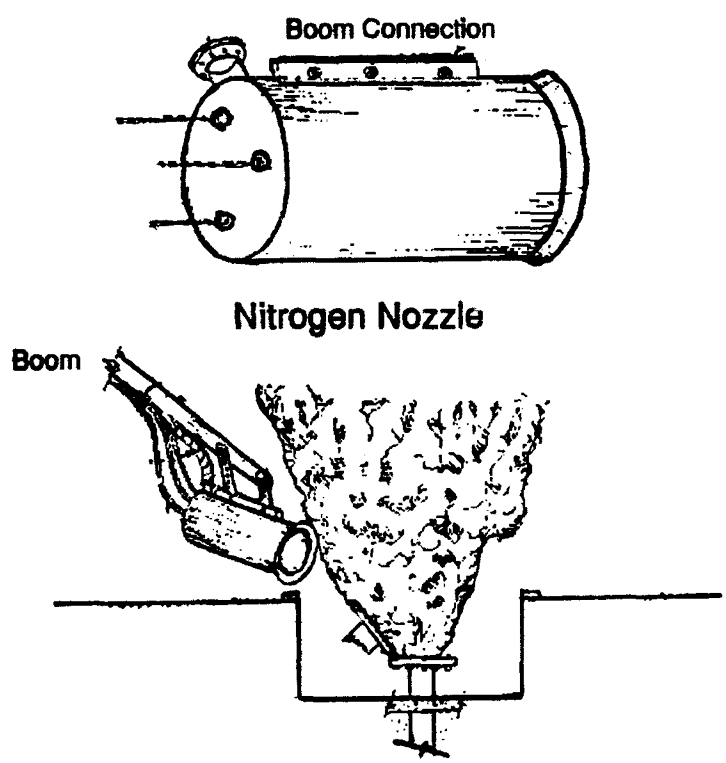

Figure 37. Nitrogen nozzle dispenses nitrogen and a dry chemical powder to cool the area around the well head (World 1991)

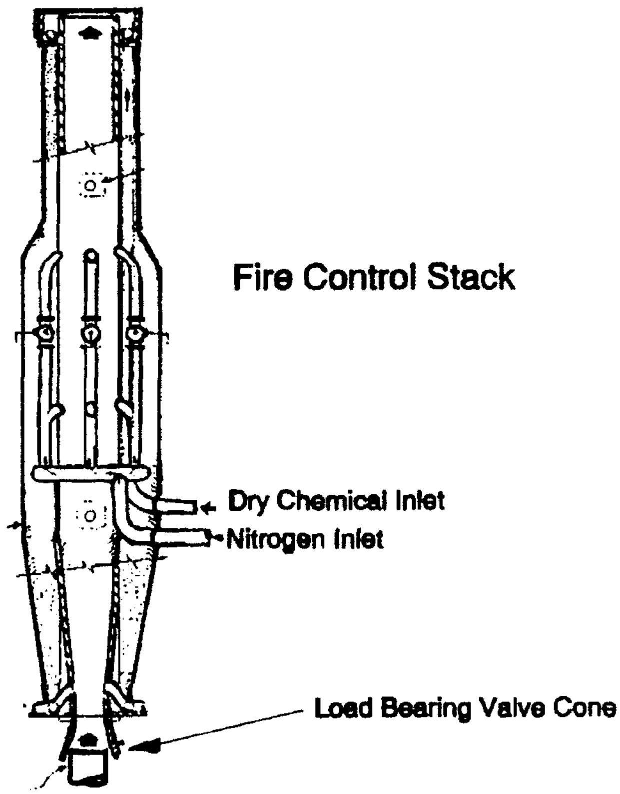

Figure 38. Nitrogen and dry chemicals are injected via the Oilwell Fire Control Stack (World 1991)

Research physicists at the University of Dayton in Dayton OH suggested the use of an intumescent, dry powder formulation of phosphate salts, sugar, urea, and pneumatogen. The material is environmentally safe and nontoxic. The powder would be formed into small pellets which would allow "better penetration into

the flames . . . use[ing] high volume delivery systems" (Dietenberger, 1991). The pellets are dispensed using a fertilizer spreader-like commercial delivery system modified to "spread the pellets at high volume rates and velocities" (Dietenberger,991).

The International Merex Group suggested the use of a military tank-like machine (Figure 39). It has two separate nozzles. One nozzle dispenses dry powder agents to extinguish the fire while the other nozzle simultaneously dispenses chemical foaming agents to cool the earth and prevent reignition. It carries 500 liters of dry chemicals and 11.8 cubic meters (m^3) of water to be mixed with 1.8 cubic meters of foam. It can deploy the combination of foam and dry chemicals from as far away as 80 meters (HyCon, undated).

Cerera GmbH, a firm located in the former Soviet Union, offers a similar device mounted on a T-55 tank chassis. It carries 10,000 liters of water, 250 liters of sulfuric acid, 2,500 liters of polymer resin, and has a foam component tank that holds 1,000 liters. The pump and cannon dispense the mixture of foam at a rate of 60 liters per second (Proposal, 1991).

The same company has a powder spraying vehicle (Figure 40) that carries 6,000 kg of dry agent that can be dispensed at a rate of 30 kg/second from a distance of 30 meters (Proposal, 1991).

A less portable version employing a similar technology was proposed by the Ahmed Ali Badoghaish Project Development Office and was called the

Multi System Combatment (MSC) (Badoghaish, 1991). Twelve units would be required for each well. Each unit consists of a star-shaped array of 12 pipes (Figure 41), each attached to water pumps capable of pumping 400 gallons per

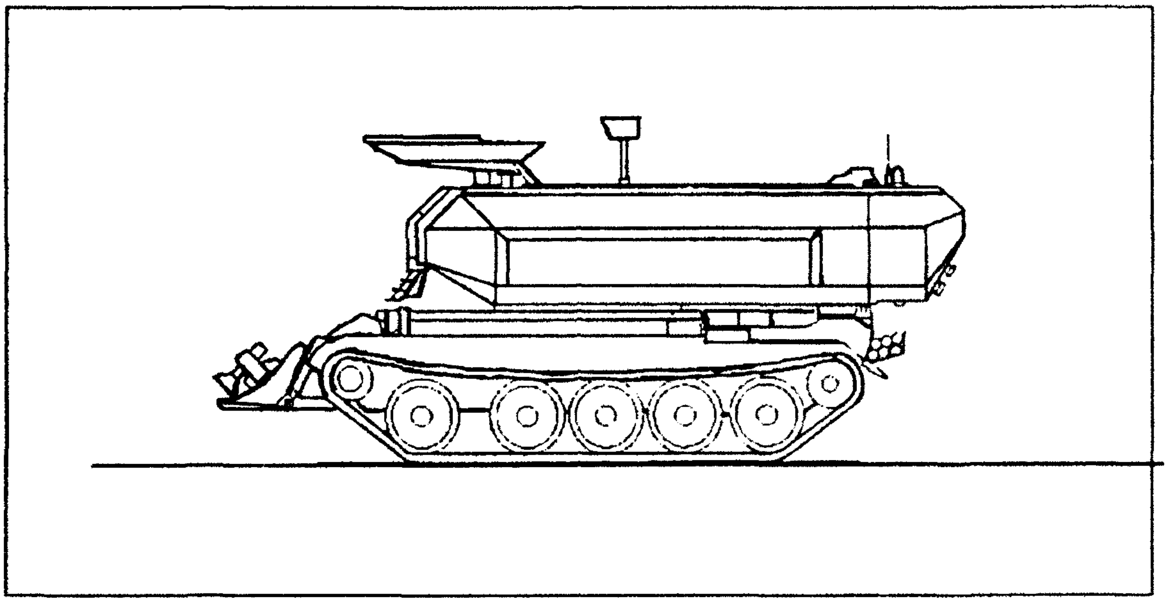

Figure 39. SPOT-55 firefighting tank dispenses foams to cool the well head area and dry chemicals to kill the fire (HyCon, undated)

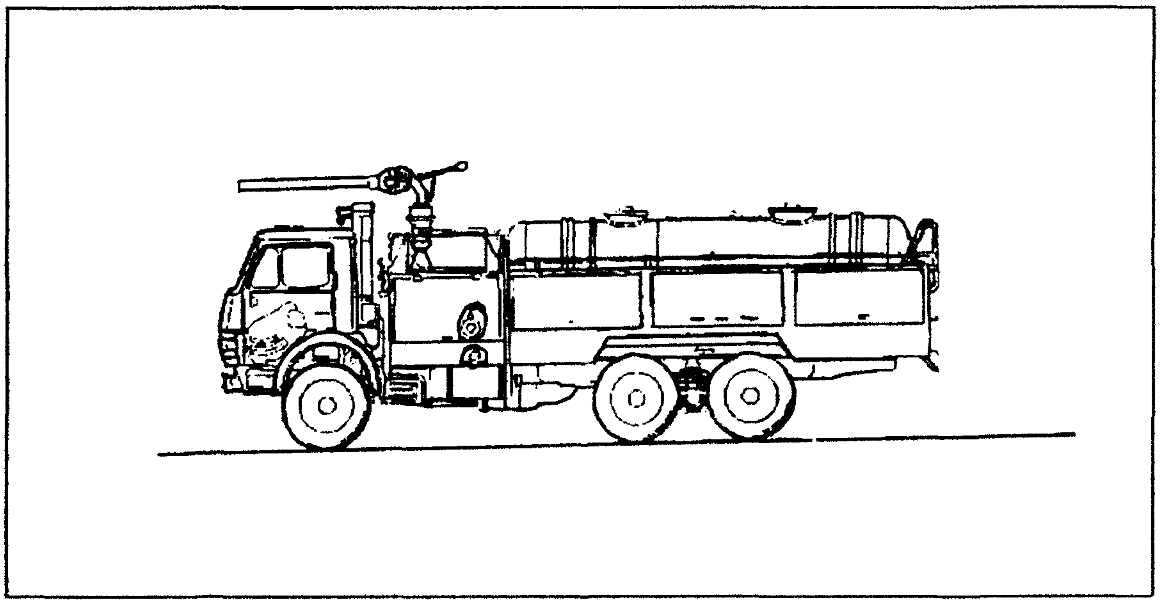

Figure 40. Dry chemical dispensing vehicle (Proposal, 1991)

minute to 12 large fans. The fans deliver "approximately 400 m^3 per minute at 3300 meters per minute velocity" (Badoghaish, 1991:2). Injectors would pump liquid detergent and carbon dioxide (CO_2) into the water

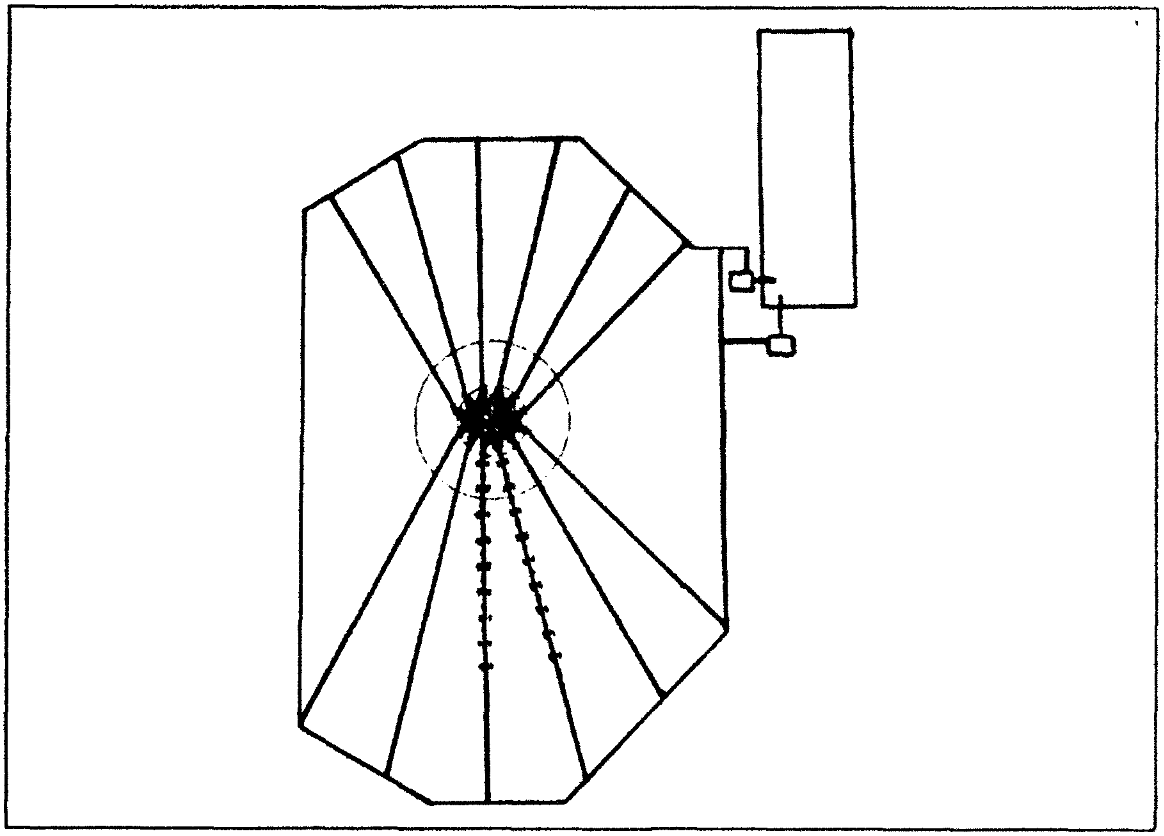

Figure 41. Multi System Combatment pyramid-shaped device dispenses CO_2 or dry agents with foam through large fans (Badoghaish, 1991)

prior to passing the water through the fan. When the mixture leaves the fan, it passes through screens that convert the mixture into foam. Some of the exhausted foam would be aimed at the base of the flame and some at the top of the flame. Between the two, the supply of oxygen is curtailed, and the heat is absorbed and dispersed resulting in extinguishment with no reignition.

A variation of this option uses a dry chemical such as ABC Sodium bicarbonate ($NaHCO_3$) in place of the CO_2 as the substance injected into the mixture. After mixing, the combined agents pass through the fans. "These dry chemicals are known for their superior oil fire extinguishing capabilities and are readily available in large quantities" (Badoghaish, 1991:4). This system delivers five tons of the chemical per minute through the fans; more than enough to extinguish the fire. The water and foam mixture cools the area around the oil well head while the agent extinguishes the flames.

This system is capable of delivering adequate quantities of dry chemicals to extinguish the fire while using only 20 - 25 percent of the water required by conventional methods (Badoghaish, 1991:7).

Ground Launched Agents. The New Mexico Engineering Research Institute (NMERI) developed a long-range fire suppressant delivery system. Instead of building a traditional device that streams the agent to the target, they developed a catapulting delivery system. It is a computer-controlled air cannon (Figure 42) that can fire six 35-pound agent-filled spherical polyurethane canisters a distance of over 1400 feet in rapid succession (McCarson, 1990:i-v). "The basic concept for dispensing the agent relies on the canister bursting upon impact in front of the burning object and the agent then sweeping across the fire" (McCarson, 1990:105). The development of this system has been limited to the fielding of a prototype. Future development, if

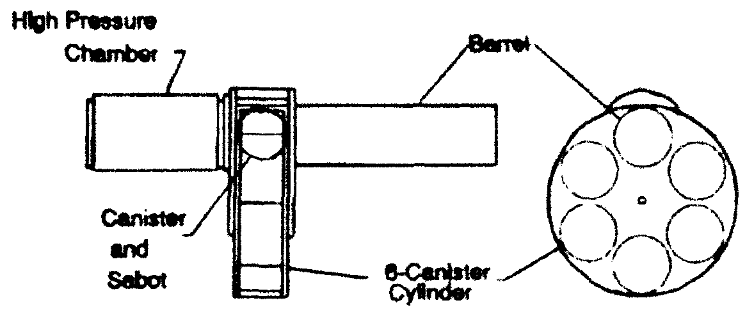

Figure 42. Long range dry chemical delivery cannon with multi-shot capability to launch spherical canisters (McCarson, 1990)

continued, may take the work of the NMERI scientists and incorporate it into a complete fire suppression system.

Another powder cannon was offered by Cerera GmbH. This cannon (Figure 43) is mounted on pipe skids and uses one big shot of a dry chemical agent instead of multiple small-load shots. It is pneumatically powered and fires a 200 kg load of "Pirant" which is the Soviet brand name for a formula having phosphorous-ammonia salts and ammonia-sulphate (Proposal, 1991).

Two different organizations, Cerera GmbH and the Minister for Military Complexes and Conversion of the Ukrainian Government, offered similar proposals for use of a conventional T-62 military tank with a system of fifty,

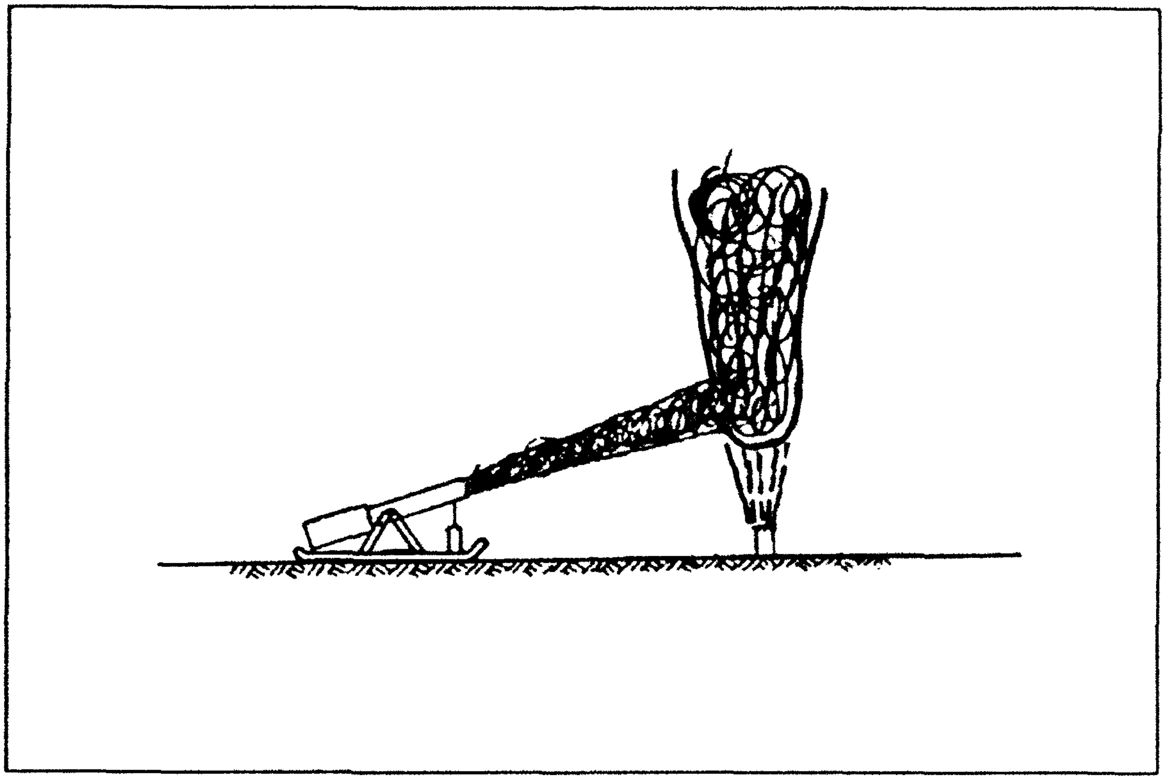

Figure 43. Pneumatically powered single-shot cannon fires dry chemical agents (Proposal, 1991)

201 mm rocket launching tubes in place of the main gun turret. "Each tube fires a non-propelled powder rocket . . . " (Proposal, 1991). The rocket is 1,000 mm long and 200 mm in diameter, and it carries 20-30 kg of dry chemical agent (Pirant). The rocket is launched by an exploding black-powder shell that is electrically detonated. The velocity of the powder when it leaves the tube is 200 m/sec, but it slows rapidly (Buxton, 1991:4). "The force of the powder being fired creates an 'impulse' wave in front of the powder as air is pushed forward in front of the mass of particles. This impulse helps to penetrate the flames" (Buxton, 1991:4).

Up to ten tubes may be fired simultaneously and can be followed closely by four additional ten-tube firings. The number and orientation of tubes fired can be varied to address the type of pattern required.

Analysis of Chemical Application Technologies.

Chemical Agents. Like explosive technologies, the use of chemical agents to suppress fires is not new to the military. Some of the agents that were once popular are no longer feasible for use, specifically the halons. The existing attributes of halons have few of the necessary properties to both extinguish oil well fires and meet environmental standards. The primary requirements are that the material extinguishes the fire, absorbs a significant amount of heat, and is not hazardous to either the workers or the environment. The selection of a particular "best agent" is beyond the scope of this research; not so with delivery methods.

Air Delivered Agents. The skills, equipment, and support equipment are available, and the air delivery of agents is a part of the U.S. military repertoire. A significant problem derives from the volume of agent required to extinguish the fire and the limited capacity to carry sufficient amounts of agent in a single bomb. It is difficult to effectively and simultaneously strike a target with multiple munitions in an effort to overcome this capacity limitation (Sikes, 1992).

Another problem associated with air delivery methods is that convection from the fire may create a turbulence so great as to displace and disperse the agent cloud from the fire. This could reduce the agent concentrations enough to render efforts ineffective (Tapscott, 1991).

Winds also have the potential of creating a significant problem. If the winds are calm, agents can cool the surrounding area and prevent reignition before they are dispersed. However, if there are either high winds or the agent selected is not particularly effective at cooling the area around the well head, the cloud may extinguish the fire and then be blown away, allowing reignition from hot materials near the well head (Renick, 1991).

Mechanically Inserted Agents. The Blaze Buster proposal gives little information about the mechanics of the delivery device or the chemicals themselves (Manders, 1992). However, the equipment is not yet fielded, and this agent delivery method requires substantial equipment and skills not currently in the military's inventory.

The Empire Armor proposal has all of the same limitations as the Blaze Buster, but it also requires conventional access to the well head. Additionally, it requires an undisclosed type of chemical agent and a significant amount of expensive nitrogen.

The University of Dayton proposal has never been experimentally proven even in the laboratory. It requires substantial time and funds for research and

development, just to determine if fielding of the system is feasible. Based on the proposal, the necessary skills, primary equipment, and support equipment are not resident in the military.

Streamed Agents. The International Merex Group's fire extinguishing tank, as well as the similar version offered by Cerera GmbH, appear to answer both the fire suppression and ground cooling questions. A variant of this system exists in U.S. military inventories, and a prototype of an armored vehicle that delivers foaming agents was developed by a joint Army/Air Force effort (U.S. Army, 1991). These however, are designed for pooled petroleum fire suppression. The amount of follow-on R&D required to modify U.S. equipment to develop this capability is significant.

The powder spraying vehicle offered by Cerera GmbH falls into the same category. It too is a new technology to the military for which there is no existing training or equipment support.

The Badoghaish MSC proposal is the star configuration of piping and fans into which are pumped CO_2 or dry chemicals. It has only been designed and no additional R&D or prototype investment has been made in a fielding effort. The system requires injectors, fans, pumps, piping, and a myriad of hardware not in the military inventory. It also requires training that is not currently available. The system described is quite complex; maybe more so than is supportable in the field. It requires six days to set up and employ the

system, which exceeds the criteria for expediency. Further, the MSC places personnel required to install and operate the system too close to the fire with insufficient safety protection.

The Badoghaish MSC proposal insists that significantly less water would be used than by conventional methods, but it still requires nearly 800,000 gallons per fire extinguished. This method uses non-polluting, biodegradable chemicals. It also needs a significant amount of CO_2 which could be provided by "a low quality grade CO_2 generator using diesel fuel as the feedstock (raw-material)" (Badoghaish, 1991:3). Less raw material is required if the dry chemical option is employed.

Ground Launched Agents. The NMERI six-shot agent launcher is not a fielded piece of equipment, and there is no current training or support equipment. Rapid reloading of the device must also be developed. Automated targeting systems need to be developed which will combine data such as exact distance, winds, and canister weight into the firing equation. The entire system needs to be mounted on some type of a mobile platform (McCarson, 1990:106-107).

The skid-mounted powder cannon is a fielded and proven system. It, or a variant of the system, has been used successfully in the former Soviet oil fields for ten years (Proposal, 1991). This equipment is not in the U.S. military inventory and would have to be acquired. An option might be to develop a

canister munition for an existing U.S. system, leveraging existing skills and equipment.

The last delivery system, the tank-mounted multiple rocket launcher meets all but one of the criteria set forth in Chapter III. It is in the military inventory, and the training is available to maintain and operate it. The dry chemical agent is readily available, and a modest modification to a munitions contract could result in an off-the-shelf capability.

The application of chemicals as a technology has spawned numerous methodologies attempting to apply chemical agents onto or into oil well fires. The choice of agent determines the amount of chemical and water, if any, required to cool the area surrounding the well head. The agent's ability to either remove the heat or chemically produce gases to displace the oxygen varies by agent type and the mixture of oil and gas in the flame (Buxton, 1991).

<u>Description of the Electrostatic Field Technology</u>. Considerable research continues on the effects of energy fields on the combustion process. Studies have included the effects of gravitational, magnetic, acoustical, turbulent, microwave, and electrostatic energy fields. Empirical studies have shown that an electrostatic field is the optimal energy field for fire extinguishment (Jonas, 1990:15).

Although the only application of this technology has taken place in the laboratory, the development of this technology is promising. Consistent

laboratory results show that when a flame is in the presence of high-voltage electric field, extinguishment occurs (Jonas, 1990:20).

The technology consists of creating an electrostatic field that encompasses the flame. Experiments have been done using the flame of a Bunsen burner. Electrodes are placed such that the flame is between the electrodes. While many electrode configurations have been tried, the most effective configuration is that of a cylindrical electrode as the negative electrode with the burner itself as the positive electrode (Call, 1991:21). Figures 44 and 45 show the dual-plate configuration and the cylindrical configuration, respectively.

In the Bunsen burner experiments, extinguishment occurs at voltages of 5 to 7.5 kV (Figure 46).

> As the voltage was increased, at a certain threshold current would start to flow. As the voltage increased so would the current, until at a certain voltage, which at first look appears independent of gas flow rate, the luminous part of the flame disappears and the maximum current, the saturation current j_s, was reached. (Call, 1990:12, 19, 20)(Figure 47)

The physical mechanisms by which the fire is extinguished are not fully understood; however, two possible explanations exist: the creation of an ionic wind and chemical effects due to altered energy states.

> Ionic wind is the movement of radicals and neutral gases due to the electrostatic forces on the radicals and their subsequent collisions with the neutral gases. (Call, 1990:21)

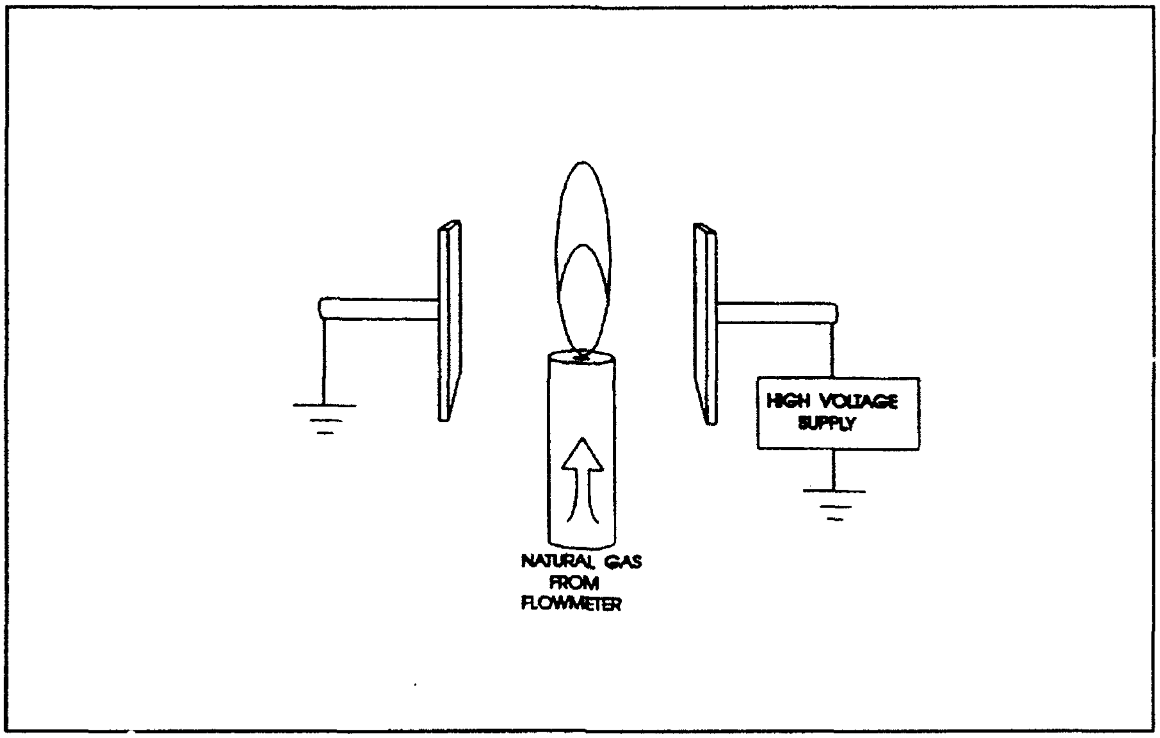

Figure 44. Dual-plate electrode configuration

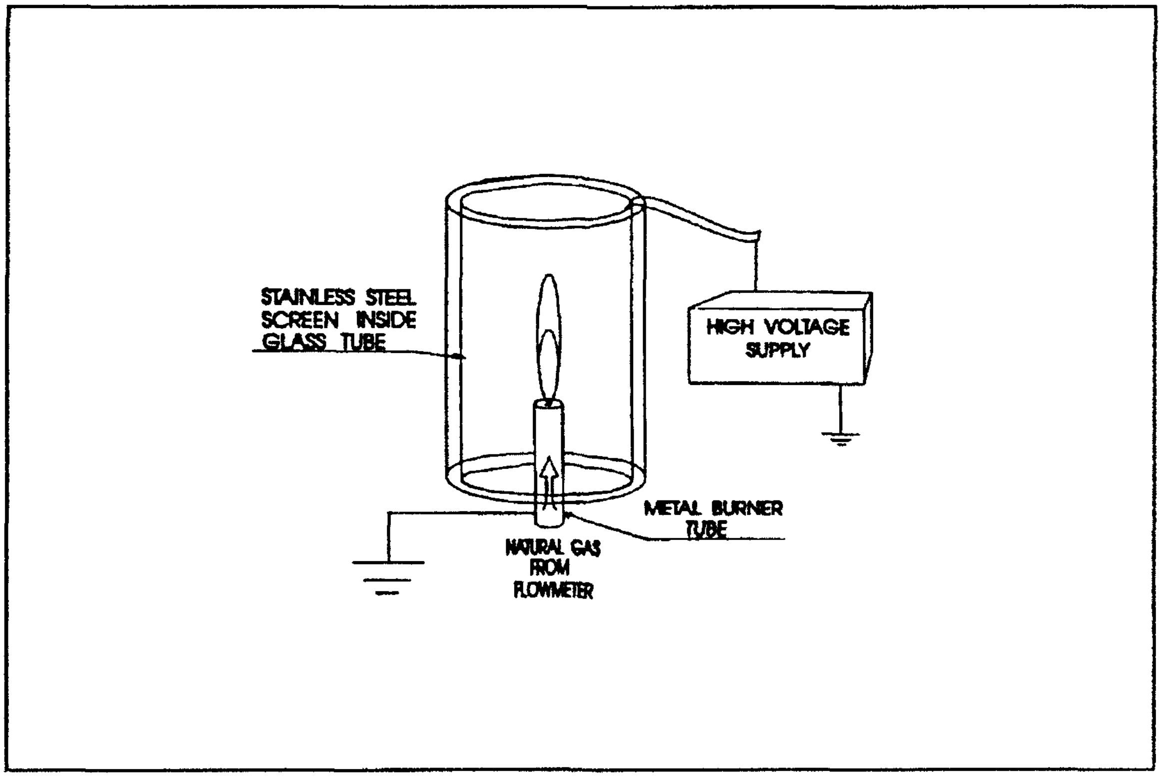

Figure 45. Cylindrical electrode configuration

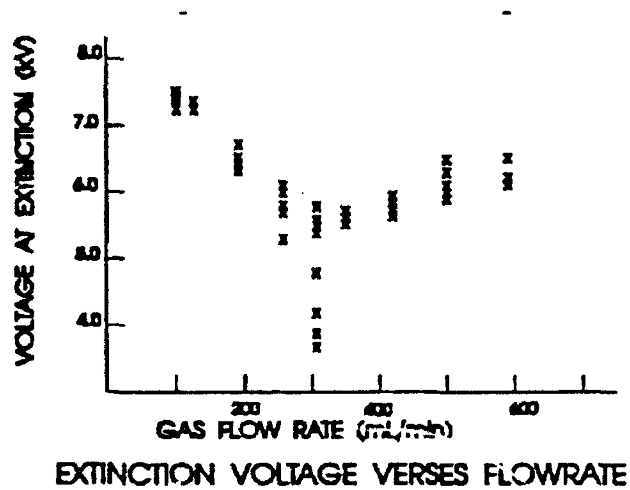

Figure 46. Extinction voltage verses flowrate (Call, 1991:20)

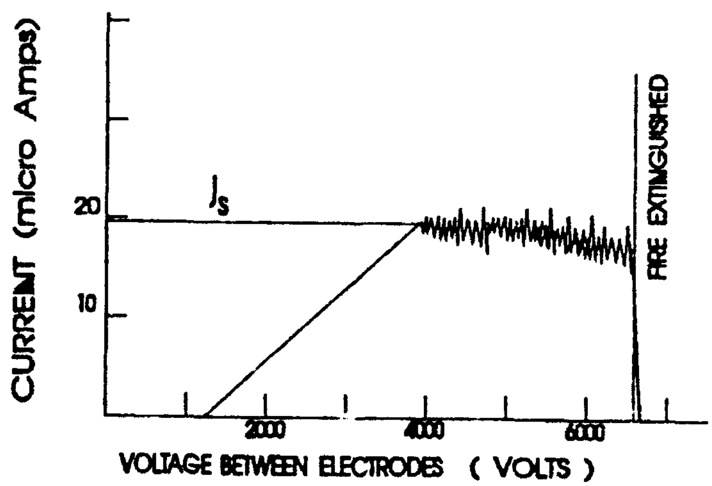

Figure 47. Current versus voltage (Call, 1991:12)

> The chemical effect described is one which aids in combustion. Energy is added to the combustion process by an electric field by raising the energy level of the free electrons which is then ultimately transferred to O_2, increasing the reaction rate of the branching chain reaction and thus the overall combustion rate. (Call, 1990:21)

The electric field strips the radicals from the reaction zone, thereby decreasing the number of radicals available and possibly interrupting the combustion reaction. Also, this effect reduces the flame temperature and reduces the combustion rate.

Analysis of the Electrostatic Field Technology. This technology is in the infant stages of development. Much study is needed yet to gain a full understanding of the mechanisms that inhibit or interrupt the combustion process. This fact prohibits the inclusion of the electrostatic energy field technology into the decision matrix.

It remains to be determined if a flame of the magnitude of a burning oil well would react in an electrostatic field in the same way that the comparatively minuscule Bunsen burner flame reacts. The relationship between the size of the flame and the required extinguishing voltages cannot be extrapolated from experimental data.

The equipment that must be developed for the employment of the electrostatic field technology would be quite different from any currently used by the DOD. It follows that the skills required to operate this equipment would also not be comparable with skills currently maintained by DOD forces.

Although the equipment necessary to employ the electrostatic field technology has not been designed or developed, the process of erecting large electrodes in the hazardous environment of the burning well requires much attention. The electrode configuration must be precise, and the dangerous environment precludes rapid construction of the system. Therefore, the use of electrostatic fields do not meet the criteria for rapid employability.

Constructing the system in extreme temperatures poses the same problems associated with conventional technologies. Vortex tubes, heat shields, and water monitors are necessary for this work. This support equipment is not maintained by the military; and therefore, does not meet the criteria requiring militarily-compatible support equipment.

Although not one of the primary criteria, an additional concern associated with the employment of the electrostatic field technology is that of reignition. An electrostatic field causes extinguishment at the well outlet but does not affect the surrounding environment where temperatures are hot enough for reignition. This means that this technology would have to be employed in conjunction with other methods of cooling the area around the well. This would entail the application of water or other coolants.

The idea of fire extinguishment in the presence of an electrostatic field is a hopeful method of fire extinguishment. However, the results of this analysis do not make its inclusion into the decision matrix reasonable.

Description of the Freezing Technology. The petroleum and gases that are extracted from oil wells contain moisture that will form ice if refrigerated. Engineers propose the application of a heat exchanger around the well casing (Figure 48). Due to its inertness, liquid nitrogen is used as a refrigerant to create an ice plug in the production string (Fairfax, 1991;Freeze, 1991). The principle behind the creation of an ice plug is the stimulation of hydrate growth within the production casing. Three conditions are necessary for hydrate growth: a sufficient amount of gas entrained in the petroleum; a sufficient amount of moisture in the petroleum; and sufficiently low fluid temperatures.

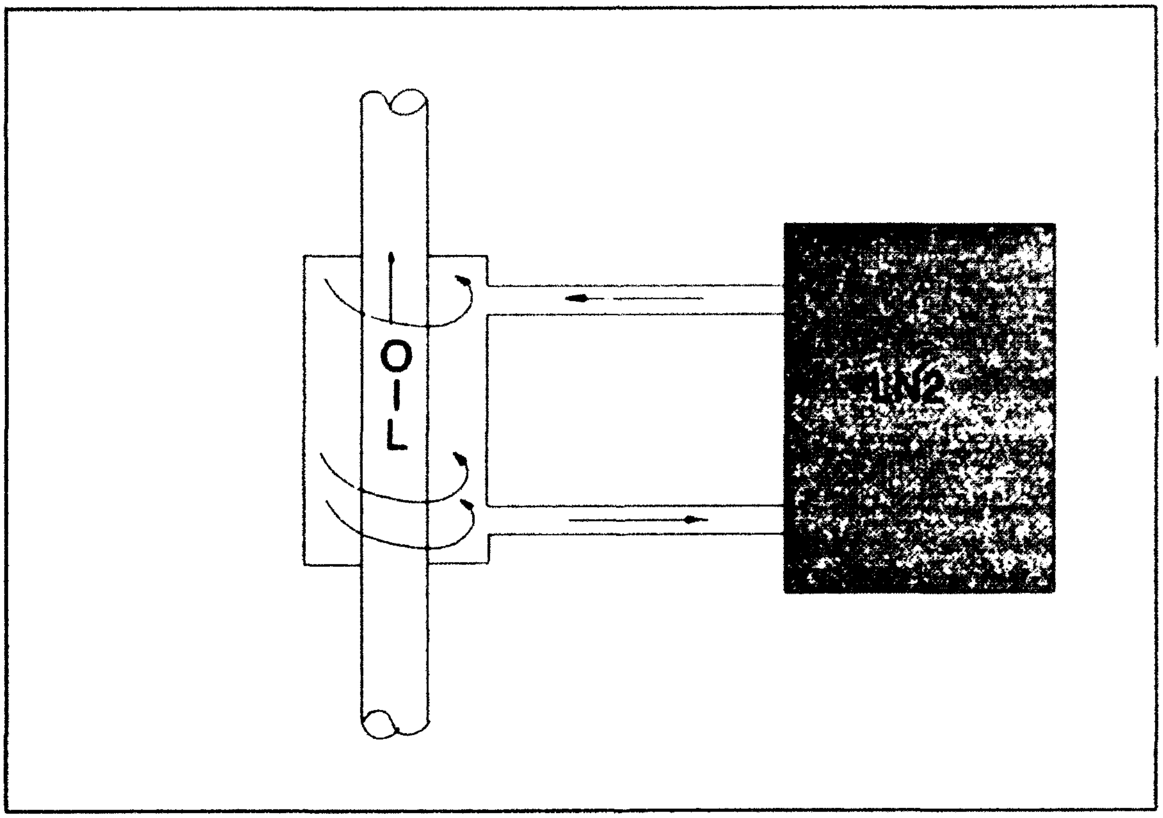

Figure 48. Heat exchanger applied to well casing (Fairfax, 1991)

Many existing oil wells operate under the first two conditions; however, the temperature of the flow is too high to stimulate hydrategrowth. The application of the heat exchanger creates the third condition. Using the heat exchanger to lower the temperature of flow induces hydrate growth starting in the outer annulus of the production casing. As the growth continues into the production string, the flow becomes constricted until a complete ice plug is formed. The ice plug prevents further flow of petroleum through the production string, and without fuel at the combustion zone, the flame is extinguished.

Analysis of the Freezing Technology. The freezing concept requires a system for pumping liquid nitrogen to the heat exchanger installed around the well casing. Although the military works with liquid nitrogen extensively, it neither maintains a liquid nitrogen system of this sort nor does it possess this type of heat exchanger. Therefore, the requirement for the equipment and training to be compatible with current military equipment and training is not met by the freezing concept.

When evaluating the use of freezing for military employment, the first obstacle recognized is that of accessing the production casing. If tunnelling is not used, and excavation is the means of exposing undamaged casing, extensive site preparation is necessary, and personnel must work close to the burning well. In this case, the requirements for expediency and personnel safety are violated. If tunnelling is used, the skills and equipment necessary to perform this

operation must be developed within the military inventory, as tunnelling is not currently an operation performed by DOD forces. Whether using tunnelling or conventional excavation, the setup and implementation times violate the requirement for expediency. These factors lead to the conclusion that this application does not meet the criteria established in Chapter III.

Description of the Hot Tapping Technology. Hot tapping stops the flow of oil and gases below the surface just as freezing does. The hot taps are designed to facilitate access to the production string to choke off the flow of oil and extinguish the burning well.

The production string is accessed from the side of the production casing by drilling through a ball valve assembly that is attached to a sleeve unit mounted to the outer production casing (Figure 49). This operation requires a specially designed hot tapping machine that allows the drilling to take place while still controlling the flow of oil. Once each successive casing is penetrated, the penetration is sealed by grouting the annulus with cement. When the production string has been successfully penetrated, the ball valve and the hot tapping machine control the flow of oil at the tap.

Two taps are made, one above the other. When both taps have been completed, a rod is inserted into the production string through the higher tap to choke the flow of oil. Steel balls and other sealing materials are then injected into the lower tap and are carried up to the rod by the flowing oil. The balls

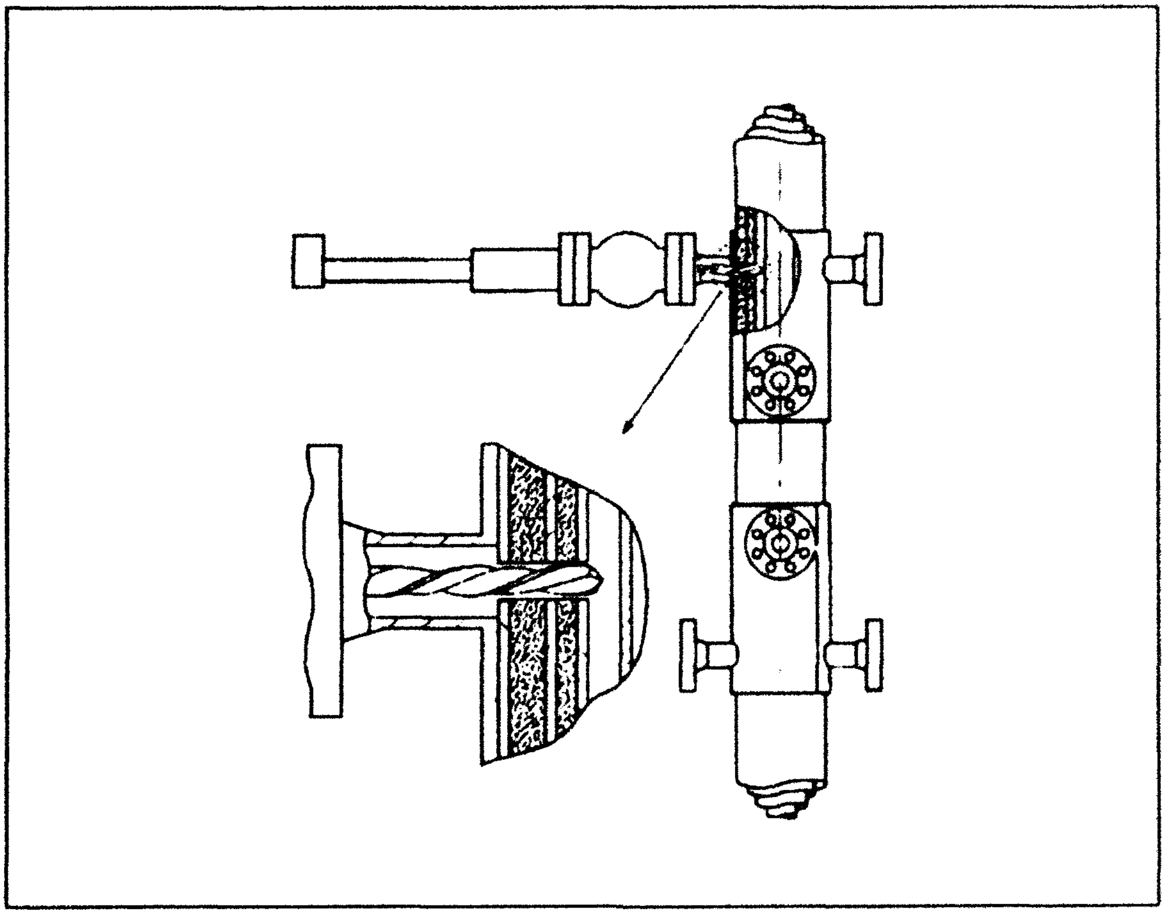

Figure 49. Hot tap penetration (Allied, undated)

are stopped by the rod, forming a plug. The oil flow is completely choked off, and the fire is extinguished (Figure 50).

Analysis of the Hot Tapping Technology. An analysis of the use of hot tapping reveals the same conclusions that were reached by analyzing freezing. This application requires specialized equipment and training. It also requires direct access to the undamaged well casing. Excavation puts personnel in dangerous proximity to the well head. Tunnelling precludes the dangers associated with operating at the well head; however, tunnelling would require

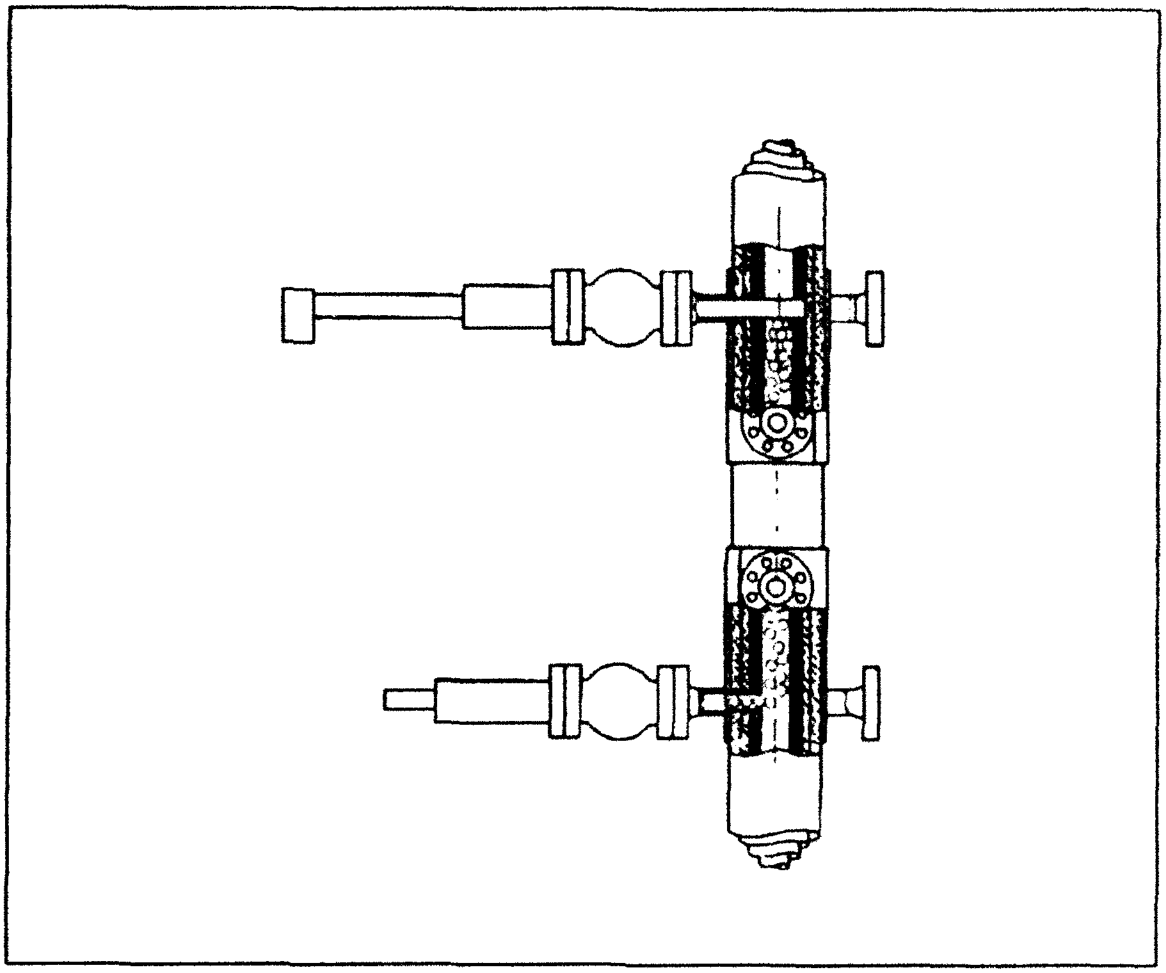

Figure 50. Plug formation through two hot tap penetrations (Allied, undated)

the introduction of a complex technology not currently maintained by DOD forces. The need to access the well directly slows the operation. This violates the requirement for rapid employability.

As with freezing, these facts make the development and maintenance of hot tapping capabilities impractical for the military.

Description of the Hood Technology. Various configurations of hoods or domes have been designed to snuff out oil well fires (Figure 51a,b, and c). The

basic principle of this technology is to merely deprive the combustion process of oxygen by lowering a large hood over the flame (Taylor, 1991). The hoods are designed large enough to allow the unit to be placed over the christmas tree and other damaged hardware (RAK, 1991).

The hoods, typically conical, have large valves at the top of the cone to permit the oil to continue to flow unobstructed through the hood. Within the dome, spray nozzles may be included for administering fire suppressants to aid in extinguishing the flame (RAK, 1991;Taylor, 1991). When the dome is properly in place, the large valve is closed to effectively snuff the flame (RAK, 1991)(Figure 52).

When the fire is extinguished, the result is a tremendous flow of unburned petroleum. The high-pressure flow of oil imparts great forces on the dome. The configuration of the dome serves to dissipate the energy associated with the flowing oil (Holding Bros., 1991;Van Roll, 1991). The gases (methane and hydrogen sulfide) may be separated, vented, and then flared to relieve pressure within the dome and prevent further hazards associated with the volatile gases (Lawrence, 1991). Once the fire is extinguished, the oil is diverted and piped into vast, lined holding reservoirs where tankers collect and transport the petroleum for refinement (Von Roll Ltd., 1991). Insufficiently large reservoirs result in uncontrolled pooling of oil and increased environmental damage.

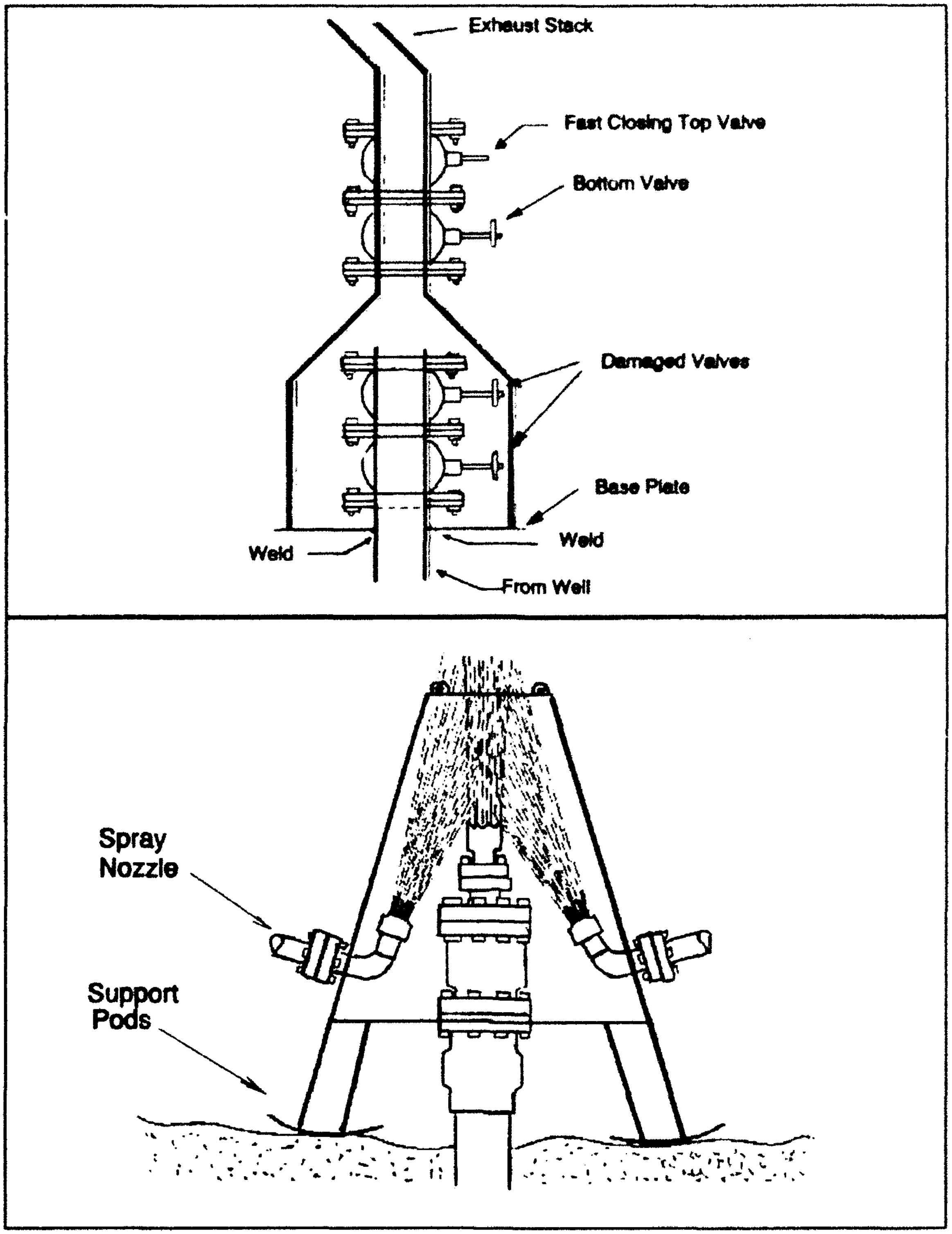

Figure 51a and b. (a) Hood design with 45-degree exhaust stack and welded into place. Proposed by SGM Worldwide Inc. (SGM, 1991). (b) Hood supported by pods using spray nozzles. Proposed by Wildland Services, Inc. (Wildland, 1991)

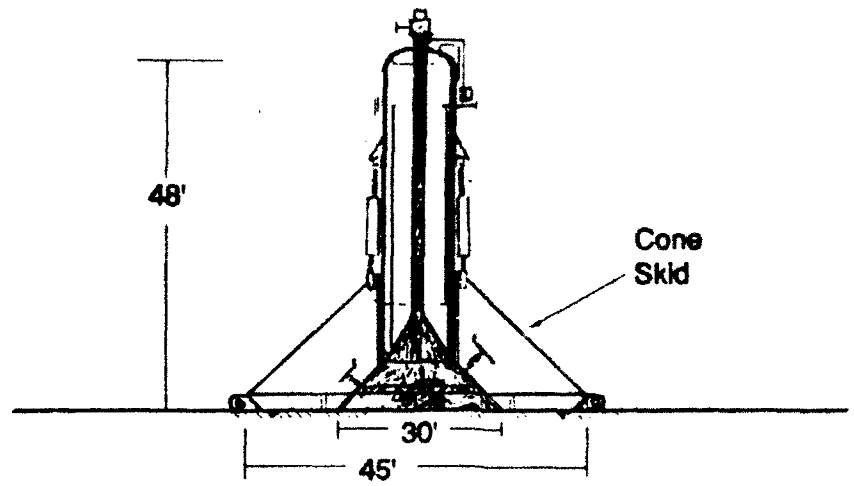

Figure 51c. The Anderson Snuffer proposed by RAK Petroleum Services, Inc. (RAK, 1991)

Analysis of the Hood Technology. Approximately 25 percent of all non-conventional proposals reviewed for this research involved the use of hoods of various configurations. While on the surface this concept appears simple, several obstacles preclude military employment.

While very little research and development is necessary to employ this technology, extensive procurement and logistics efforts are necessary to field such a system for military use.

Many of the hood configurations require a flush seal with the ground at the base of the hood; other configurations use a tripod base for support. The area around the well must be cleared of coke and debris and leveled to support

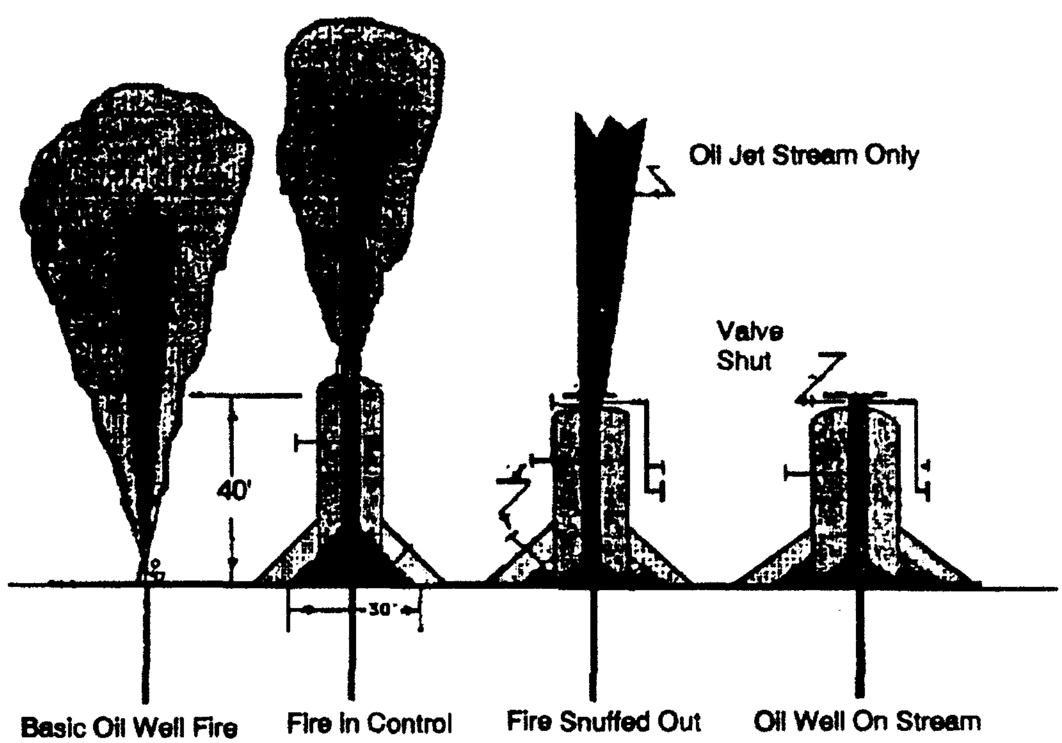

Figure 52. Typical sequence of operations using the hood application (RAK, 1991)

the hood. Athey wagons, heat shields, and water monitors are required for the coke-clearing operations. This equipment is used in conventional technologies and is not currently in the milita, inventory.

Description of Wind Blast Technology. The arid climate of the Middle East and the great demand for water in oil well fire fighting operations make the logistics for obtaining water a major issue. In the research conducted by Jonas, he notes from Layman that, "the rate of heat absorption [for water] can be increased by increasing the surface exposure . . . " (Jonas, 1990:11). Further, the "surface exposure of a given volume of water can be increased by breaking the water into finely divided particles" (Jonas, 1990:11). This principle led to the development of an ingenious piece of firefighting equipment that proved to be successful for the Hungarian government on five of the Kuwaiti oil well fires (Nova:1991). Similar systems were proposed by the German Consortium for Blowout Control and Cerera GmbH (German,1991:34; Proposal, 1991).

The equipment consists of gas turbine engines mounted on a military truck or tank. The Hungarian unit consists of two MiG-21 engines mounted to a T-34 tank (Bernstein, 1991:16)(Figure 53). The system proposed by the German consortium consists of MiG-21 engines mounted to a T-55 AMZ tank (German, 1991:34). The Cerera GmbH system uses a jet engine mounted on a truck (Proposal, 1991).

The jet exhaust is directed at the burning oil well, and water is injected into the exhaust outlet of the jet engine. The water is atomized to achieve a maximum surface area and, therefore, a maximized heat absorbing potential. The atomized water serves to cool the burning well while the inert exhaust gas

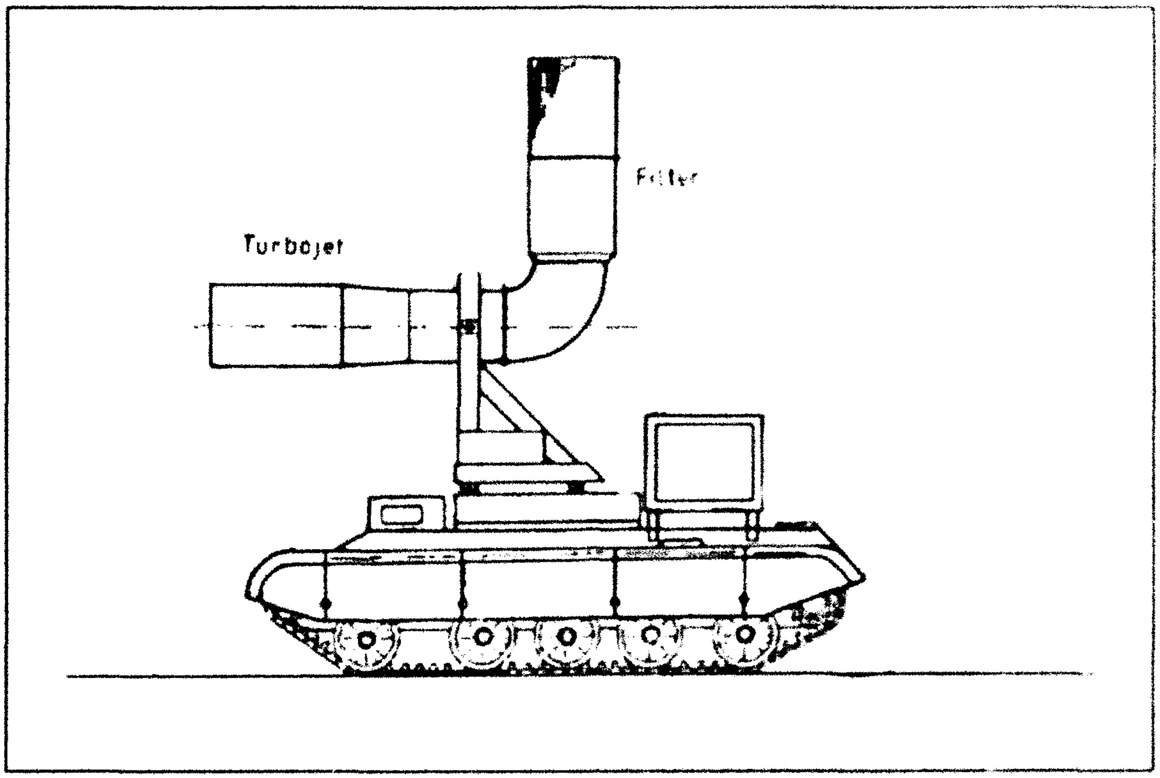

Figure 53. Wind blast vehicle consisting of jet engines mounted to a military tank frame (German, 1991)

displaces the oxygen from the flame (German, 1991:34). The jet exhaust not only cools and extinguishes the oil well fire, but it also cools the area surrounding the well to prevent reignition.

<u>Analysis of Wind Blast Technology</u>. A major drawback associated with this application is the effort necessary for development and procurement. The components of these firefighting systems (trucks, tanks, and jet engines) may be found in DOD procurement channels; however, the design, procurement, and fielding of such equipment represent significant cost and effort.

This piece of firefighting equipment requires the operation and maintenance of trucks, tanks, and jet engines. The military possesses and maintains these types of resources, i.e., Army personnel are adept at maintaining and operating trucks and tanks, and Air Force personnel are trained to operate and maintain jet engines. These facts make the application of these systems appealing.

Vehicle-mounted jet engine firefighting systems afford a safe, hands-off approach to oil well fire suppression allowing the operators to remain safe inside the vehicle, away from the burning well. The truck and tank running gear allow the equipment to navigate the rough terrain associated with this scenario.

This equipment has weight and dimensions similar to conventional tanks and trucks. This means that the vehicle may be readily transported by wide-bodied aircraft.

Analysis of Methodologies Using Ancillary Criteria

When reviewing the feasibility of the methodologies, it is conceivable that two may be equally viable. In situations of this nature the ancillary criteria should be considered to assist in the decision-making process. These criteria are stopping the flow of oil and minimizing damage to the well.

A number of the methodologies suppress the smoke, but the flow of oil continues unchecked. From the commander's perspective, when the fire is

extinguished and the smoke is eliminated, his objectives are reached. However, the environmental medium carrying the pollution burden is shifted from air to land with a four hundred fold increase in volume. The increased environmental damage caused by the unburned oil is severe enough to warrant reignition of the well once the targets obscured by the smoke have been eliminated.

The increased damage caused by the unburned oil speaks to the value of using a fire suppression method that results in stopping the flow of oil. The use of air-delivered munitions certainly provides the required crimp, but it so severely damages the well cellar and well casings as to virtually destroy the well. From an oil production perspective this should be prevented if possible.

Therefore, when one or more methodologies measure equally against the nine primary criteria, the ancillary criteria should be used to determine the ideal solution. An ideal solution is one that meets all nine primary criteria, stops the flow of unburned oil, and results in minimum damage to the well.

Conclusion

In this chapter, twenty-one methodologies were described and analyzed to determine if they were employable by the military to suppress oil well fires in accordance with the primary criteria listed in Chapter III. A matrix of the criteria and the methodologies shows the results of the analyses at a glance. Boxes are marked to indicate primary criteria the methodology does not meet.

The suggested technology must:

1. eliminate or significantly reduce smoke
2. have low R&D, design, and fielding costs
3. fall within the scope of existing training
4. use existing militarily-compatible equipment
5. be durable and field worthy
6. be portable, highly mobile and air-transportable
7. be rapidly employable, once in place
8. apply the above criteria to support equipment
9. keep workers at a safe distance from the fire

TABLE 1. TABLE SHOWING FAILED CRITERIA FOR EACH METHODOLOGY

	CRITERIA								
TECHNOLOGY	1	2	3	4	5	6	7	8	9
Crimping									
- Explosive									
-- Surface									
--- MSG Int'l		X	X					X	X
--- HydoCut		X	X	X				X	
-- Sub-surface									
--- Air Delivery									
--- Drilling			X	X			X		
--- Digging								X	X
--- Hybrid		X	X	X				X	X
- Mechanical			X	X				X	X
Chemical									
- Air Delivered		X							
- Mech Inserted									
-- Blaze Buster		X	X	X				X	
-- Empire Armor		X	X	X				X	X
-- Univ. Dayton		X	X	X				X	
- Streamed									
-- Int'l Merex		X		X					
-- Carera Tank		X		X					
-- Carera Truck		X		X					
-- MSC		X	X	X	X		X	X	X
- Launched									
-- NMERI		X	X	X				X	
-- Cannon		X		X					
-- MRL		X							
ESF		X	X	X			X	X	X
Freezing			X	X			X	X	X
Hot Tapping				X	X		X	X	X
Hoods		X		X				X	
Wind		X							

V. Conclusions and Recommendations

Introduction

This chapter provides a synopsis of the thesis effort. The starting premise is restated followed by a narrative of how the course changed during the process of researching and writing the thesis. Next is a restatement of the criteria and a listing of the methodologies ranked by the number of criteria that were not met. The discussion of the research section explains the need for and the expected value of this research and also points out some limitations for use. This is followed by a discussion of the areas of the additional research that might be investigated to expand this thesis effort. Finally, the conclusion provides a brief overview of the entire effort.

Background

This research effort began with the sincere belief that the development of a decision support matrix to assist commanders was an important and achievable goal. In the beginning the list of technologies and situational factors or conditions was manageable. However, as the descriptions of the technologies began to unfold, the number of significantly different variations increased the number of methods under consideration increased by nearly 300 percent. The criteria were developed and stated in Chapter III. Twenty-one fire-suppression methods were analyzed individually. The result was contrary to

expectations since the number of methods that met the criteria was exceedingly small. Only one method resulted. The criteria were then reevaluated to ensure that they were valid and reasonable. Reinspection determined that they in fact were relevant. This resulted in a search for another medium with which to describe the results. This was important because a matrix with only one intersection was suspected of being of limited value to commanders (the client). In search for an alternate medium, a listing of the methodologies analyzed in this research was chosen.

The list has, at the top, the methodology that met all of the criteria. It is followed by those methodologies that are feasible if one criteria was relaxed. The next method on the list is the recommended choice if two criteria were relaxed. That pattern continues until either all the list is exhausted or the number of criteria that were relaxed was so high that the option became illogical to consider.

Listing of Methodologies

The following is an abbreviated version of the criteria from Chapter III, followed by a list of the methodologies analyzed.

The suggested technology should

1. eliminate or significantly reduce smoke,
2. have low R&D, design, and fielding costs,
3. fall within the scope of existing training,

4. use existing militarily compatible equipment,

5. be durable and field worthy,

6. be portable, highly mobile and air transportable,

7. be rapidly employable, once in place,

8. apply the above criteria to support equipment, and

9. keep unprotected workers at a safe distance from the well.

Next is the list of the methodologies discussed in Chapter IV. They are ranked by counting the number of criteria not met by a given methodology. The results are presented in descending order of feasibility.

- Air-delivered munitions used to crimp production string	- Met all criteria
- Multiple rocket launcher with chemical dry-agent rounds	- Met all but criteria 2
- Wind-producing vehicles	- Met all but criteria 2
- Air-delivered chemical agents	- Met all but criteria 2
- Carera Tank	- Met all but criteria 2 and 4
- Int'l Merex Tank	- Met all but criteria 2 and 4
- Dry-agent cannon	- Met all but criteria 2 and 4
- Dry agent dispensing truck	- Met all but criteria 2 and 4
- Digging to place explosives	- Met all but criteria 8 and 9
- Hoods and domes	- Met all but criteria 2,4, and 8
- Drilling to place explosives	- Met all but criteria 3,4, and 7

- NMERI sphere cannon	- Met all but criteria 2,3,4, and 8
- Mechanical crimping	- Met all but criteria 3,4,8, and 9
- U. Dayton pellet spreader	- Met all but criteria 2,3,4, and 8
- HydroCut crimping method	- Met all but criteria 2,3,4, and 8
- Blaze Buster chemical delivery	- Met all but criteria 2,3,4, and 8
- MSG Int'l vortex tube crimping system	- Met all but criteria 2,3,8, and 9
- Oil freezing system	- Met all but criteria 3,4,7,8, and 9
- Hot tapping methods	- Met all but criteria 4,5,7,8, and 9
- Hybrid crimping methods	- Met all but criteria 2,3,4,8, and 9
- Empire armor's agent injection stack	- Met all but criteria 2,3,4,8, and 9
- Electrostatic field generator	- Met all but criteria 2,3,4,7,8, and 9
- MSC star-shaped chemical applicator	- Met all but criteria 2,3,4,5,7,8, and 9

This list shows that the preferred choice of methodologies that can be employed immediately is the air-delivered munitions used to crimp the oil well production string. This methodology is the only one that meets all nine criteria. If criteria 2 is relaxed, three more methodologies would be feasible. They are the multiple rocket launcher with chemical dry-agent rounds, jet engines on vehicles, and air-delivered chemical agents. Five more methodologies are acceptable if two criteria are relaxed and the remaining fourteen methodologies fail to meet three or more of the criteria.

Recommendations for Further Research

Additional research could be accomplished by determining the amount, cost, and depth of research required to field these methodologies. Of special interest are those in which a research and/or development effort is required to either test the proposal or allow it to be fielded. Researchers could replace the bimodal evaluation of the methodologies with a weighted-criteria evaluation. This would help to quantify the effort required to make the technologies employable by the military. With additional effort, researchers could establish a threshold past which pursuit of the technology becomes impractical.

It is to the economic advantage of the military to extend the life of its weapons systems as much as possible. This must be balanced against the need for the U.S. to maintain technological superiority over its adversaries. Quantification of the costs necessary to field a smoke-suppressing technology may reduce the urgency required to field the new all-weather weapons.

Conclusion

Prior to the beginning of Desert Storm, the Chief of Staff of the Air force asked his staff for an assessment of the operational impacts oil well fire smoke was expected to have on the employment of precision-guided munitions. He also asked for an assessment of the U.S. military's capability to counter the threat. Prior to the Gulf War, the body of knowledge within the services was extremely limited, so the information search was expanded to include the U.S.

civilian sector. Because of the imminent war the time available to the Air Staff for this research was extremely limited. The answers given to the Chief of Staff were rapidly formulated and indicated the U.S. military had little capability to counter the projected adverse impact the smoke would have on air operations.

With the war over and more time available, this thesis was undertaken to expand the body of knowledge on this subject. The search for technologies that might be employed by the military to suppress oil well fire smoke was expanded beyond domestic resources and ultimately became international in scope. Through interviews with military experts and firefighters, a set of situational factors affecting the employment of these technologies was developed. Technologies for extinguishing oil well fires were investigated by conducting interviews, studying research data, periodical literature, and proposals for the control of Kuwaiti oil well fires.

Over 200 proposals from the Kuwaiti disaster and four technologies from the R&D community were reviewed. The feasibility of military employment in a combat environment was determined through a bimodal evaluation of methodologies using nine criteria. Only one methodology met the criteria. The compilation, description, and analysis of data is a unique compendium of knowledge. The information resulting from this thesis will provide the basis for developing considered answers to questions similar to those asked by the Chief of Staff - should the need again arise.

Bibliography

Air Base Survivability Systems Management Office Headquarters, Armament Division, Air Force Systems Command. Air Base Camouflage Techniques. October 1984.

Al-Rahmani, Mahmoud A., Deputy Chairman and Deputy Managing Director, Planning and Development. Personal interview. KuwaitiForeign Petroleum Exploration Corporation, Kuwait City Kuwait, 26 April 1992.

Allied Oil Control Group. Kuwait Oil Well Intervention - A Proposal by the Allied Oil Control Group for a Below the Surface Side Entry Blow-Out Control. Proposal submitted to the Kuwaiti Petroleum Corporation for oil well firefighting, presented by Trade Link Kuwait EST, Kuwait City Kuwait.

Badoghaish, Ali Ahmed. Multi System Combatment "MSC" (Introductory Proposal), Ahmed Ali Badoghaish Project Development Office, Kuwait City Kuwait, April 1991.

Bernstein, Amy. "Flameout," US News and World Report, (11 November 1991)

Blow-Out-Stop System For Surface And For Underground Application. Technical Description. Battelle-Institut e.V., Battelle Europe, Frankfurt am Main Germany, August 1991.

Bretz, Lt Col Thomas E, Jr., Division Chief. Telephone Interview. Phillips Laboratory, Shock Physics Division, Kirtland AFB NM, 4 November 1991.

Bretz, Lt Col Thomas and Dr. Jerry Leigh. Shock Physics Division of the Phillips Laboratory, Kirtland AFB NM and New Mexico Engineering Research Institute. Operation Smoke-Out. White Paper, 7 March 1991.

Bretz, Thomas E. Jr. and Joseph D. Renick. A Nonconventional Means For Controlling Kuwaiti Oil Field Fires. Phillips Laboratory, Shock Physics Division, Air Force Systems Command, Kirtland AFB, NM, 10 April 1991.

Buxton, Stephen, Kuwait Oil Fields - Fire Fighting. SB Offshore Group, Edinburgh, England and Ove Arup & Partners Consulting Engineers, London, England, July 1991.

Call, T. and D. Schwartz. Electric Fields for Flame Extinguishment: Interim Report on In-House Research, June 1991 - December 1991. HQ AFCESA, Tyndall AFB FL, December 1991.

Canby, Thomas Y. "After The Storm," National Geographic, 180: 2-33 (August 1991).

Component of files and documents transferred from the possession of Lt Col Thomas E. Bretz, Jr., Chief, Shock Physics Division, Phillips Laboratory (AFSC), Kirtland AFB NM to Capt Richard D. Taylor, AFIT, School of Engineering and Services, Wright-Patterson AFB OH, 13 December 1991.

C.O.R.T. PROJECT. Hydro Cut Proposal. International Hydro Cut Technologies Corporation, North Vancouver, British Columbia, Canada, undated.

Development and Demonstration of a Prototype Nonconventional Technique for Controlling Oil Wells Using Explosive Effects Technology. Test Plan. Shock Physics Division, Phillips Laboratory (AFSC), Kirtland AFB NM, 6 June 1991.

Dietenberger, Mark A. and Ival O. Salyer. Concept Paper on Oil Fire Suppression Using University of Dayton Fire Extinguishing Technology, University of Dayton Research Institute, Dayton OH, 19 July 1991.

Explosive Assisted Oil Well Control. Report. Phillips Laboratory (AFSC), Shock Physics Division, Kirtland AFB NM, 24 April 1991.

Fairfax Construction Company. Fire fighting proposal sent to the Kuwaiti Petroleum Corporation. Troy MI, August 1991.

Fleck, John. "Bombs Can't Snuff Kuwait Well Fires, Official Says," Albuquerque Journal, B2 (May 3, 1991).

Floden, Captain John, Senior Fire Research Scientist. Telephone Interview. Air Force Civil Engineering Support Agency, Research Division, Tyndall AFB FL, 25 Oct 1991.

Floden, Capt John R. and Dr. Robert E Tapscott. "The Quest for Chemical Alternatives to Halon 1211," The Military Engineer, 537: 13-15 (August 1990).

Freeze Oil Crimp Technique. Kuwait Oil Well Control Proposal Using the Freeze/Oil/Crimp System. Michael Stewart Group International, Nottingham, England, 29 August 1991.

Garwin, Richard L. and Henry W. Kendall. "Quenching the Wild Wells of Kuwait," Nature, 354:11-14 (November 1991).

German Consortium for Blowout Control. Extinguishing - Killing - Capping - Securing of Oilwells. Proposal submitted to the Kuwaiti Petroleum Corporation. Frankfurt, Germany, July 1991.

Hatteberg, Richard, Well Control Specialist. Telephone interview. Red Adair Company, Dayton OH, 1 Nov 1991.

Holding Brothers/WS Atkins International Limited. Well Fire and Flow Control for Immediate Resumption of Production: Reinstatement of Kuwait's Oil Production, Surrey, England, August 1991.

Horgan, John. "Up in Flames," Scientific American, 264: 17-24 (May 1991).

HQ PACAF/DOU. Camouflage, Concealment, and Deception Training. undated.

Hughes Aircraft Company. Maverick Operations Supplement, IR Maverick. Supplement MAV-M-1060-3. Field Support Engineering, Tucson AZ, July 1988.

Hughes Aircraft Company. Maverick Operations Supplement, TV Maverick. Supplement MAV-M-1000-2A. Field Support Engineering, Tucson AZ, June 1987.

HyCon. SPOT-55, The Extinguishing Tank. Defense Security Progress, International Merex Group, Buschhof GE, undated.

IMAX Film Production. Hellfighters of Kuwait, Smithsonian Air and Space Museum Premier, 6 Mar 1992.

Johnson, D.W. and others. "Airborne Observations of the Physical and Chemical Characteristics of the Kuwait Oil Smoke Plume," Nature, 353:616-621 (17 October 1991).

Jonas, Dr. L.A. and J.S. Steel. Energy Fields for Fire Extinguishment, August 1989 - February 1990. Contract F08635-89-C-0381, Report Number ESL-TR-90-11. Wheaton MD: Hughes Associates, Inc., August 1990.

Lawrence Livermore National Laboratory (LLNL). Firefighting Technical Brief, University of California, Livermore CA, 26 August 1991.

Leabo, Jim, Well Control Specialist. Telephone interviews. Wild Well Control Inc., Wright-Patterson AFB OH. 5 December 1991, 6 April 1992.

Limaye, S. S. and others. "Satellite Observations of Smoke from Oil Fires in Kuwait," Science, 252: 1536-1539 (14 June 1991).

Manders, Stephen, President. Telephone Interview. Blaze Busters Inc., Dickinson ND, 13 May 1992.

McCarson, T.D. Jr. et al. New Concept Firefighting Agent Delivery System: Final Report, February 1986-September 1990. Contract F29601-85-C-0129, Report Number ESL-TR-91-04. New Mexico Engineering Research Institute, University of New Mexico, Albuquerque NM, November 1990.

McPeak, General Merrill A., Chief of Staff, USAF. Briefing notes for the Gulf War Summary on CNN, undated.

Parry, Neal, Chairman, Fire Suppression Task Force. Personal Interview. Sante Fe International Corporation, Alhambra CA, 6 March 1992.

Petrovic, Stojadin and Joze Duhovnik. Elaborate on Extinguishing and Closing of Oil Wells Afire in Kuwait, Litostroj Corporation and Exploengineering - Litostroj, Ltd, Djakoviceva 36, Slovenia, Yugoslavia, August 1991.

Phillips, Major Gregory P., Chief of Electronic Combat Mission Planning. Telephone Interview. Force Assessment Division, Directorate of Plans and Operations, Pentagon, Washington DC, 4 February 1992.

Project For Kuwait's Oil Well Fires, A. The High Technology Solution to Extinguishing Oil Well Fires and Capping Oil Wells. Blaze Busters, Inc., Dickinson ND, May 1991.

Proposal for Fire Killing and Oil Well Recapping in Kuwait. Soviet Proposal. CERERA GmbH, Vienna, Austria, 25 June 1991.

RAK Petroleum Services. Inc., Firefighting Proposal, Sharjah, United Arab Emirates, 27 June 1991.

Red Adair Company, The. The Red Adair Company. Company Brochure, Houston TX, undated.

Renick, Joseph D., Technical Advisor for Weapons Environments Branch. Personal Interview. Phillips Laboratory, Shock Physics Division, Kirtland AFB NM, 13 December 1991.

Robertson, Maj James S. "FastFACs in the KTO: The First Combat Test of the F/A-18D," Marine Corps Gazette, 76: 86-95 (May 1992).

SGM Worldwide Inc. Proposed Oil Well Firefighting Technology and Equipment, Doran Oil Well Unit No.1, Fort Lauderdale FL, 20 August 1991.

Sikes, Major Roy B., Chief, Tactical Warfare Force Planning. Personal Interview. Force Assessment Division, Directorate of Plans and Operations, Pentagon, Washington DC, 6 Mar 1992.

Simms, Danny, Senior Vice-President. Personal interview. D&S Well Service, Cody WY, 12 Dec 1991.

Smith, William C. and Roy A. McCrory. "Comparison of Electro-optical Sensor Performance Measurements and Model Prediction in Nonideal Weather: Preliminary Results," Electro-optical Technology for Autonomous Vehicles, Proceedings of the Society of Photo-Optical Instrumentation Engineers, 219: 34-40 (February 1980).

Tactical Air Forces, TAF 401-91, Mission Need Statement for an Adverse Weather Precision Strike Capability. Joint Requirements Oversight Council validated requirement 15 March 1992. Langley AFB VA: Tactical Air Forces, 30 September 1991.

Tapscott, Dr. Robert E., Division Manager. Correspondence. New Mexico Engineering Research Institute, Advanced Protective Technologies Division, University of New Mexico, Albuquerque NM, 4 April 1991.

Tapscott, Dr. Robert E., Division Manager. Telephone Interview. New Mexico Engineering Research Institute, University of New Mexico, Albuquerque NM, 19 February 1992.

Taylor, Capt Richard D., An Assessment of the Operational and Environmental Impacts of Smoke from Burning Oil Wells. Point paper to Secretary and Chief of Staff of the Air Force. HQ USAF, Washington DC, 1 October 1990.

Taylor, Robert E. Well Blowout Control Proposal, Proposal submitted to the Kuwaiti Petroleum Corporation, 8 September 1991.

Tucker, Wesley, Project Engineer, OPERATION SMOKEOUT. Personal Interview. Shock Physics Division, Phillips Laboratory, Kirtland AFB NM, 13 December 1991.

Tusa, Francis. "There's More to Smoke Than Smacks the Eye," Armed Forces Journal International, p.36 (April 1991).

"UNEP Coordinates Effort to Survey Ecological Devastation in Kuwait," Journal of the Air & Waste Management Association, 41: 978 (July 1991).

U.S. Army TACOM and Engineering and Services Laboratory. Armored Personnel Carrier (APC) Firefighting Vehicle System. Final Report ESL-TR-91-09. Air Force Engineering and Services Center, Tyndall AFB FL, 21 March 1991.

Van Roll Ltd. Procedure to Extinguish and Close Burning Oil Wells in Kuwait, Amended Version, Zurich, Switzerland, 13 June 1991.

Wadley, Raymond C., Superintendent of Post-Capping Operations Division. Personal Interview. Kuwaiti Oil Company, Ahmadi Kuwait, 25 April 1992.

Warden, Colonel John A. III., Special Military Assistant. Telephone interview. Office of the Vice-President of the United States, Wright Patterson AFB OH, 27 Nov 1991.

WGBH Educational Foundation. "The Hell Fighters of Kuwait," Nova, Public Broadcasting, 12 July 1991.

Wildland Services, Inc. Letter proposing the Injector Bell to the Kuwaiti Petroleum Corporation. Reno NV, 8 August 1991.

World Wide. Fire Dousing Project Kuwait 1991. Empire Armor, Inc., Sussex, England, 1991.

Vita

Captain Richard D. Taylor was born on 17 July 1952 in Bozeman, Montana. He attended high school in Cody, Wyoming and subsequently earned a Bachelor of Science in Business Administration at Montana State University in Bozeman, Montana. Upon graduation and commissioning, he was assigned as a Missile Launch Officer at Whiteman AFB, Missouri. He stayed at Whiteman AFB after that assignment and served as Food Service Officer, Operations Officer and Squadron Commander, all in the Services Squadron. He moved to Decimomannu AB, Sardinia where he was assigned as Chief of the Combat Support Element. At the conclusion of that tour he returned to the CONUS to Headquarters CENTAF at Shaw AFB, South Carolina. As Director of Housing and Services, he planned and exercised war plans in Southwest Asia. He subsequently moved to the Pentagon in Washington DC where he was the Support Systems Analyst for the Directorate of Plans and Operations. While in Washington DC, he completed a Master of Science degree in Human Resources Management. In May 1991, he moved from the Pentagon to Wright-Patterson AFB, Ohio. There he entered the School of Civil Engineering and Services at the Air Force Institute of Technology in the Graduate Engineering and Environmental Management program.

Permanent address: c/o 3431 South Pacific Hwy #134
Medford , Oregon 97501

Vita

Captain William B. Owens was born on 7 May 1960 at Ft. Leonard Wood, Missouri. He graduated in 1978 from Plant City High School in Plant City, Florida. He later attended the University of Florida in Gainesville, Florida. Upon graduating in August 1987 with a Bachelor of Science in Mechanical Engineering, he was assigned to the 22d Civil Engineering Squadron, March AFB CA. During his four-year assignment he worked as a design engineer (DEED), Chief of Readiness (DEMO), and Chief of Heavy Repair (DEMH). He also served as the Base Civil Engineer at Seeb AB, Sultanate of Oman during the Gulf War. After returning from the war in April 1991, he entered the School of Civil Engineering and Services at the Air Force Institute of Technology, under the Graduate Engineering and Environmental Management program.

Permanent address: c/o P.O. Box 2883
Brandon, Florida 33509

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	22 Sep 92	Master's Thesis

4. TITLE AND SUBTITLE

AN ASSESSMENT OF THE OPTIONS AVAILABLE TO AIR FORCES' COMMANDERS TO SUPPRESS SMOKE FROM OIL WELL FIRES

5. FUNDING NUMBERS

6. AUTHOR(S)

Richard D. Taylor, Captain, USAF
William B. Owens, Captain, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology, WPAFB OH 45433-6503

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GEE/CEC/92S-16

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The particulates in smoke from oil well fires can obscure targets and inhibit the use of precision-guided munitions. The purpose of this research was to develop a decision support matrix to aid commanders of air forces select methodologies for controlling oil well fire smoke through fire suppression. Through interviews with military experts and firefighters, a set of situational factors affecting the employment of these technologies was developed. Technologies for extinguishing oil well fires were investigated by conducting expert interviews and studying research data, periodical literature, and proposals suggesting means to control the Kuwaiti oil well fires. Over 200 proposals from the Kuwaiti disaster and four technologies from the R&D community were reviewed. The feasibility of military employment in a combat environment was determined through a bimodal evaluation of methodologies using nine criteria. Only one methodology met the criteria; diminishing the practicality of a decision matrix. The decision matrix was replaced by a ranked list of methodologies. Further research is necessary to replace the bimodal evaluation with a weighted-criteria evaluation of the methodologies. Researchers could quantify the effort required to make the methodologies employable by the military and establish a threshold past which pursuit of the technology becomes impractical.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Smoke, Oil Well Fires, Obscurants, Precision Guided Munitions, Fire Suppression	129
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL